Visual Elements In Flight Simulation

Committee on Vision

Assembly of Behavioral and Social Sciences

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VISUAL ELEMENTS IN FLIGHT SIMULATION

Report of Working Group 34

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Assembly of Behavioral and Social Sciences
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COMMITTEE ON VISION

Working Group 34

Members

John Lott Brown, (CHAIRMAN), University of Rochester

William Benson, (EXECUTIVE SECRETARY), NAS-NRC Committee on Vision

H. Richard Blackwell, Institute for Research in Vision

Carter Collins, Smith-Kettlewell Institute of Visual Sciences

J.W. Gebhard, The Johns Hopkins University, Applied Physics Laboratory

Richard Held, Massachusetts Institute of Technology

Gene E. Lyman, National Aeronautics and Space Administration

Frederick A. Muckler, Manned Systems Sciences

James J. Regan, Naval Training Device Center

Stanley W. Smith, Ohio State University

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INTRODUCTION

Flight simulators have now been in use for many years and their value has been amply proven. The LINK trainer, which was widely used for pilot training in the Second World War, was a precursor to a variety of the much more elaborate devices used today for training astronauts and military and commercial aviators and for research and development. Many of today's simulators are far more costly than the aircraft of World War II, but they can pay for themselves by decreasing the cost and increasing the safety of learning to fly complex and expensive modern aircraft, if a sufficient amount of performance learned in the simulator will transfer to performance in an aircraft. Commercial aviation is presently very interested in using simulators to train their pilots. In addition, the use of simulators by the armed forces is extensive and increasing. Some of the most elaborate simulators in operation today have been developed for military applications.

The goal of the airlines is to reduce to an absolute minimum the amount of time spent in aircraft for training. In addition to reducing opportunities for serious accidents, simulators are cheaper to operate than aircraft, and aircraft freed from such requirements may be used to produce revenue. The problem of safety is perhaps even more important in preliminary training in some military problems, such as air-to-air interception and low level attack flights, which are more hazardous situations than those encountered in commercial aviation. Simulators continue to play an important role in research and development, but most of this work is sponsored by NASA or other government research laboratories.

The relative importance of simulation-training in commercial aviation varies greatly from one company to another. The acceptance of simulators is increasing, however, and a number of the maneuvers required for FAA certification may be learned in simulators. Some maneuvers still must be learned in aircraft, but the number for which this is required has been decreasing. How many maneuvers must actually be practiced in the air varies with the particular airline, depending on the airline's simulation capabilities and the specific aircraft. Many of the maneuvers that must be demonstrated in actual flight deal with asymmetrical thrust, which results from loss of one or more engines on one side of the aircraft and hence involves severe motion effects. These are difficult to simulate but involve a certain amount of hazard when performed in aircraft. It would, therefore, be desirable to improve simulators to the point where such maneuvers could also be learned and demonstrated in simulators.

Some aspects of aircraft control depend upon an exterior view from the aircraft of the outside visual world. Training in these aspects of flight in a simulator therefore requires that the visual world be simulated to the extent that cues derived from it need be employed by the pilot. Maneuvers of particular importance involve landing, take-off, and the circling maneuvers associated with these operations. Attempts

to provide highly realistic simulations of the external visual world are fairly recent in the history of aviation. Instrument flight is generally conceded to be somewhat more difficult than direct visual contact flight, and the simulation of a functioning instrument panel is very much easier than simulation of the external world. Therefore, it has been reasoned that the direct visual contact simulation need not be included, for if a pilot can learn to fly an aircraft on instruments alone, he should be easily able to transition from instrument flight in a simulator to direct visual contact flight in the aircraft. In point of fact, there are a number of maneuvers that cannot be performed without direct visual contact under normal circumstances in commercial as well as in military aviation. The importance of including a simulation of the external visual world is now acknowledged.

Providing good specifications for just how to simulate the external visual world is far from simple (Bliss, 1969; Lewis, 1970). An effort may be made to create a complete simulation of all possible cues that a pilot might derive from the visual world, but this is a herculean task and probably unnecessary. Unfortunately, there is currently no solid scientific basis for cataloging visual cues with respect to their importance in aircraft control. In consequence, current efforts to create appropriate visual simulations run the gamut from efforts toward almost complete replication of the visual world to highly schematized, two-dimensional perspective displays on cathode-ray tubes (CRT). There would appear to be no systematic effort to mount a coordinated assault on the problem utilizing a cooperative approach on the part of all of those agencies with a stake in its solution.

This state of affairs resulted in the creation of a working group constituted by the Committee on Vision of the National Academy of Sciences - National Research Council to study the visual simulation problem, to report on the present status of the problem, and to make recommendations on possible new approaches to solutions of visual simulation or, at least, to pinpoint areas in which more effort may profitably be expended. This report summarizes the information gathered by the Working Group and recommends research topics, techniques, and strategies that the Working Group agreed should receive more attention.

TECHNIQUES FOR THE SIMULATION OF THE VISUAL WORLD

In order to provide a simulation of the visual world, it is necessary to present the simulator pilot with a picture, the perspective of which constantly changes appropriately for movements of the aircraft. The picture must somehow be located so that it may be viewed through the wind-screen of the simulator cockpit. One of the most frequently used procedures is the location of a flat, reflecting screen outside the cockpit in such a position that it can be illuminated with a picture by a projector mounted above the cockpit and seen by the pilot within the cockpit. In most installations employed at the present time, the size and distance of the screen are sufficiently small that the view presented is optimum from only one location within the cockpit. An alternative to a screen is the use of a television picture tube viewed directly through the windscreen. The visual angle subtended by the picture from the point of view of the pilot may be increased by placing a large collimating lens between the picture tube and the observer. If the observer is at the proper distance from the lens, he will have a clear view of the tube at optical infinity (Ganzler, 1971). A problem with this system rests with the fact that there is a limited exit pupil, within which the eyes of the observer must be located in order to obtain a full and undistorted view of the scene. Some work has been undertaken on systems that will eliminate the exit pupil limitation.

Ellipsoid and spherical mirrors have also been investigated for the purpose of increasing field of view in a limited space. A slightly different system has been employed in a differential maneuvering simulator installed at the Langley Research Laboratories of NASA (Brown, 1972). In this installation, each of two simulator cockpits is located within a spherical enclosure, the surface of which is illuminated by a projector mounted on top of the simulator cockpit. Sky, ground and an horizon line are projected on the inside of the sphere and change their orientation appropriately for maneuvers introduced by the pilot. They respond only to angular motions and provide no visual simulation of linear motion with respect to the ground. A picture of another aircraft is also projected on the sphere. This is accomplished by the use of a model and camera in such a way that the orientation and relative size of the other aircraft correspond to its relative speed and the simultaneous maneuvering of the two aircraft. The primary purpose of the device is to permit two pilots to fly air-to-air maneuvers simultaneously. This is quite different from most simulators in which the main concern with visual displays is for take-off and landing maneuvers.

SOURCES OF VISUAL INFORMATION

The complexity of the visual information required in a simulation

varies somewhat with the purpose of the simulation. In the differential maneuvering simulator, ground plane and sky remain constant in terms of elements of spatial detail and change only in their orientation with respect to the simulator cockpit. The other aircraft is also constant with respect to its three-dimensional identity and changes only with respect to the position, relative size, and perspective angle of its image projected on the sphere.

For creation of the external visual world as seen by a pilot during take-off or landing, much ground detail must be provided. The most direct approach to this problem is to build a three-dimensional scale model. Such models may be extremely detailed, although limitations on the resolution of pick-up and projection equipment create practical limits beyond which further attention to detail is unwarranted. A major problem with scale models is that they are relatively large, and it is therefore not practical to change them frequently. In addition, they can represent only a very limited area of the terrain. It is difficult to provide sufficient area for a complete circling landing maneuver. Unless artificial constraints are imposed, pilots are likely to fly "out of bounds."

Some of the models are constructed on a moving belt. Thus, one dimension of translation is achieved by movement of the model relative to the pick-up camera. Such a system is manufactured by General Precision Systems (GPS), now a subsidiary of the Redifon Company in England. A similar system is under development by LINK Aviation. These systems derive from earlier systems in which an airport runway was presented on a moving belt. A television camera was moved vertically and laterally to provide changes of perspective as the belt moved under it during landing simulations.

For some limited applications, visual information may be derived from transparencies or silhouettes, which are themselves moved in relation to a point source of illumination. Shadowgraphs thus created may be quite large relative to the size of the transparency or silhouette employed. Such devices have found only limited applications.

Some form of photographic storage of visual information for use in a visual world simulation has been considered. At present, there are severe limitations on the maneuvers that can be performed with photographic simulations, however. In the VAMP (variable, anamorphic motion picture projector) system of LINK aviation, 70 mm. film is employed but only half of its frame width is viewed by the pilot in his display. The film is exposed through a wide-angle lens to further increase the azimuth angle covered from the point of view of a pilot. Changes in simulated aircraft heading are accompanied by a lateral shift of the film to provide a change in visual perspective. Changes in speed of the aircraft are accompanied by a change in the projection

rate of the film. Such a procedure is only useful when slight changes in heading will be required. One possible application is that of training in terrain clearance flights at low altitude.

Some investigation is being carried out on the possible use of holographs for visual simulation. A holograph permits a variety of views of a given object photographed by simple translation of the holograph film relative to the viewer. The angle through which view may be changed is limited by the size of the holographic plate and its distance from the object photographed when it is exposed. At present, holographs are under investigation by the Navy and may prove of limited usefulness in the creation of visual presentations of another aircraft or limited target.

ELECTRONICALLY-GENERATED DISPLAYS

A fairly realistic portrayal of the visual world may be created by an electronic system. Edges are used to depict ground terrain, objects on the ground, and objects that may move in relation to the ground. The computer stores sets of coordinates defining plane surfaces arrayed in three dimensions. Some of these surfaces may define objects such as aircraft. A two-dimensional projection of the stored information may be presented on a color television monitor from any desired aspect or distance. The number of edges that can be employed is limited by the storage and computational power of the equipment. Even with limited edges, however, fairly reasonable presentations can now be achieved. Smoothly curved surfaces such as the fuselage of an aircraft are represented by a small number of plane surfaces. Shading is achieved with variation of the brightness of individual flat surfaces. Any given surface is homogeneous with respect to color and brightness for a given perspective. Shading of a given surface may be changed with changes in perspective. Within these limits, a rather remarkable realism has been achieved with the number of edges now being used.

The amount of spatial resolution that can be achieved is limited by the number of edges employed. It is also limited by the number of scan lines employed in the television display. When the size of spatial detail represented is reduced to the order of spacing of the scan lines scintillation effects result. Similar effects may be observed · home television sets.

Straight line elements presented on these displays appear quite good when they are exactly horizontal or in line with the scan lines of the presentation. They also look reasonably good when their orientation does not deviate greatly from vertical. Unfortunately, when a straight horizontal line in the presentation begins to deviate from horizontal, as would the horizon line, for example, when an aircraft

in straight and level flight goes into a bank, difficulties arise. The line breaks up into a series of straight lines, each horizontal with respect to the television monitor. They are segments of the raster lines of the display. The less the deviation from horizontal, the longer are these segments. As a result, edges in the presentation assume a somewhat serrated appearance as they move through various orientations on the display. This limitation is slightly disturbing but not extremely serious. It will be relatively difficult to eliminate without a substantial increase in the number of scan lines employed.

In the real world, atmospheric dispersion results in a muting of brightness and color differences with distance, even in the absence of any fog or significant amounts of haze. This is called aerial perspective. A cartoon-like quality of electronically-generated displays results from the lack of any aerial perspective effect in most of these displays as presently employed. Fog and haze can be introduced electronically at the present time. Presentations in which some "fog" has been introduced appear much more realistic than those without it. A limited degrading of brightness and color with distance as this occurs in the real world can be introduced electronically in these systems. Experimental work carried out with simulated fog has demonstrated that a substantial improvement in realism of the display can be achieved in this fashion.

Advantages of Electronically-Generated Displays.

Such displays include no mechanical components, which may introduce lags or dead zones, or mechanical inertia effects, which may serve to limit the fidelity of the display with respect to relative visual motion effects. There are no mechanical restrictions on continuous, 360° rotations about any axis.

The perspective from which an electronically-generated display is observed may be from a maneuvering aircraft observing the ground, from a point on the ground, or from one maneuvering aircraft observing another. The same basic equipment and the same stored information may be employed for any of these options.

There is no serious limit on the range of flight in any direction. An almost unlimited amount of simulated terrain may be stored on tape or with any other convenient method. Such terrain can be called up and deposited in core for immediate access as the simulated aircraft travels in any given direction. Variations may be introduced fairly simply with respect to such dimensions as color, color balance, luminance, and artificial lighting. As many airports, cities, or other geographic regions as desired may be stored on tape for ready

access with a minimum of difficulty in transition from one terrain to another. Although the realism of presently available electronically-generated systems is not comparable to that provided by models, the flexibility is very much greater, and the realism may be improved substantially with presently available technical capabilities.

The most elaborate electronically-generated visual simulations available at the present time are one developed for NASA in connection with the lunar module (Lockwood, 1971) and the space shuttle vehicle (SSV) program, and another currently being developed for the Air Force. The NASA simulation is now used for the study of the space shuttle vehicle landing problem and the docking maneuver required in linking with an orbital space station. It consists of 320 edges. Its 20 Hz. scanning rate and a 600 line raster were designed to gain spatial resolution at the expense of temporal resolution. Attenuation of brightness, a result of viewing a television monitor through a large collimating lens, eliminates all evidence of temporal flicker, however. The flexibility afforded by an electronically-generated display is ideal for the relatively unique problems that must be undertaken by the space agency. On the other hand, the relatively routine training requirement of an airline for maintaining the efficiency of its pilots may argue against the use of an electronic simulation and in favor of a terrain model simulation.

A variety of hybrid systems has been considered in which models may be combined with electronically-generated presentations or film presentations. Different sources of visual information may then be employed for different parts of a flight simulation. It is then possible to take advantage of the detail afforded by a model during take-off and landing and the unlimited scope of an electronically generated display during cross-country flight. If a high order of visual detail is needed for straight and level flight, the photographic system may be used.

DIMENSIONS OF THE VISUAL DISPLAY

A Committee for Simulator Design has been concerned with the nature of variables that must be included in an adequate visual display (see Dust, 1970) as well as with the essential variables for a motion display. The limiting conditions for a minimally acceptable visual display remain a matter of some contention, nonetheless. At this time, there is not available a definitive, scientifically established basis for specifying what range of visual variables is essential, what variables might be helpful if not essential, and what variables need not be included. There is no easy way to distinguish the essential elements from those that are merely relevant and helpful. The distinction will differ in any case with different aircraft,

different situations, and different maneuvers. It would seem reasonable to adopt the position that any simulation will be enhanced to the extent that it is made more like reality, but there are practical and economic limits on the application of this approach to the problem. It may prove useful to consider various dimensions of the visual world and their possible significance in the design of a satisfactory visual simulation.

Extent of the Simulated Visual Field.

In an aircraft, the extent of the view of the outside world is limited by the size of the wind-screen or cockpit canopy. In multi-engine aircraft, it usually extends in angular measure from 190° to 220° in the horizontal dimension, and it is 26° or more in the vertical. The Committee for Simulator Design has argued that a wide field of view is essential in simulations, particularly for circling maneuvers and for the type of landing pattern employed in STOL aircraft. It is self-evident that the wider the field of view, the greater is the information immediately or potentially available to the pilot. A wide field of view is particularly important for turning and circling maneuvers to provide early information about possible obstacles and other aircraft that may be encountered when heading is changed. The spatial resolution capability of the human eye is severely limited outside of the small region of central vision so that, no matter how great the extent of the visual field, the information immediately available is relatively limited outside of the immediate vicinity of the point of fixation. With a wide field of view, the pilot can scan a much larger area, however. In addition, for any point of fixation, the relatively high sensitivity of the peripheral retina for the detection of motion as compared to its spatial resolution capability provides a rapid flow of information to the viewer concerning any new object that moves into almost any portion of the visual field. The field of view of the pilot of a rapidly moving aircraft is a continuously changing pattern. The relative visual motions of objects and surfaces within that field are a rich source of information for the pilot. The subject of visual motion will be considered in more detail later, but one may note here that the larger the visual field, the greater the potential information available from relative movements within that field. Beyond some field size, the advantages of further increases are probably negligible, but we cannot yet say what that field size is.

Studies have been conducted to determine the effect of limiting the horizontal extent of the visual field on a pilot's ability to control his aircraft satisfactorily. These studies show that a remarkable degree of reduction in field extent is possible without gross impairment of a pilot's control capability. It has been shown that limiting of the horizontal field to 22° or somewhat less, even down

to 15^{o} may be accompanied by little measurable degradation in performance. The horizontal visual field has been reduced to as little as 4^{o} in extent, but this is obviously unsatisfactory (Hasbrook, 1973). Even though studies do not show serious effects, a reduction to 15^{o} or 20^{o} is almost certainly unsatisfactory when possible situations involving other aircraft and the need to detect landmarks or other objects on the ground are considered. It has been argued that a relatively limited field of view may be quite satisfactory under circumstances where the pilot is completely familiar with the terrain over which he is flying (Moran, 1971a). This is usually the case for commercial airline pilots flying familiar routes. It is probably reasonable to assume that a significantly more limited field of view may be satisfactory in a simulator, the purpose of which is to develop familiarity with and test proficiency in the handling of an aircraft. Even under actual flight conditions, pilots are fairly frequently called upon to control their aircraft with severe limitations on the field of view. This is true in night flying with limited available luminance, and it may also be true in winter storms when the wind-screen may become coated with sticky snow outside of the wiper pattern. Of course, at night, under conditions of low visibility, a visual field of broad extent may be of increasing importance for detection of other aircraft and of landmarks under conditions of limited visibility.

The field of view in simulation of the visual world outside a simulated aircraft is almost invariably severely limited compared to the visual field available in flight. At present, the approach appears to be to make the simulated visual field as large as possible within practical limitations and not to be overly concerned by the necessary restrictions.

Range of Luminances.

The range of luminances that can be displayed in a simulation of the visual world is somewhat limited relative to the range which may be encountered in flight. This is probably not a serious concern in most circumstances, however. Information processing by the visual system depends upon the spatial distribution of relative luminance information and not upon absolute levels. Once the minimum necessary luminance levels have been achieved for efficient extraction of visual information from a display, there is little advantage in further increases in luminance. There are some special circumstances in which limitations of available luminance may be a concern. These include situations in which external illumination may be distracting to the pilot, whether its source be the sun, bright searchlights or the detonation of an atomic weapon in the vicinity of the aircraft. Special devices have been developed to simulate the latter which could be employed if these circumstances are of particular concern.

Color.

There is no question as to pilot preferences with respect to the dimension of color; pilots almost unanimously prefer color to black and white presentations in simulations of the visual world (Chase, 1971). Quantitative tests of advantages afforded by color have shown small but positive results (Chase, 1970, 1971). When color provides a significant dimension of information, as in the case of signal lights, it is obviously important. Extensive efforts to replicate the exact color conditions that exist in the visual world would probably be misplaced, however. These color relations are subject to constant change from one time of the day to the next, with changes in weather and with changes in season. Observers are quite tolerant of rather large deviations in actual color, and subjective standards of acceptability are probably quite adequate. The range of colors available on a color television monitor is probably sufficient for a simulation display, even though the range is somewhat limited relative to the full range of natural colors. Color would appear to be important in those circumstances where important information is encoded in color variations and, second, for its value in enhancing the pilot acceptance of a simulation device.

Spatial Resolution.

The human eye is capable of resolving spatial detail that subtends a visual angle of significantly less than one minute of arc at the retina. Simulated visual presentations on television monitors, on the other hand, do not afford resolution of better than six or seven minutes of arc. Somewhat better resolution may be obtained with a film presentation such as the VAMP system. The film presentations are grossly limited for other reasons. Thus, the spatial resolution capability of simulations must be recognized as a rather serious limitation relative to the capability of the human visual system. There is no definitive evidence as to how this may limit the utility of **simulations**, however. It has been suggested that the reduced spatial resolution available in simulations is a significant factor in the differences in performance between an aircraft simulation and the aircraft itself (Chase, 1971).

The resolution of a television monitor seen through a collimating system is better than the resolution of a projection system. It is also significantly cheaper to use a television monitor than a projection system. Pilots themselves prefer direct view of a television monitor over a projection system in the main.

The limit of spatial resolution may be significantly larger than six or seven minutes of arc under some circumstances. This problem relates to the level of precision employed in the construction of models. With a small scale model, there is a severe limitation on the amount of

detail that can be included. Thus, as an aircraft descends, coming closer to the object on the ground, elements of detail which would normally emerge with closer approach simply aren't there. One of the models employed at the Ames Research Center of NASA has been built on a 600:1 scale and replaces the original model which was built on a 1200:1 scale. Resolution on close approach is materially improved with the 600:1 scale.

The purposes of the collimating lenses used with television monitors is to increase the size of the visual field and the apparent depth. A problem with these devices is that the head position of the observer must be in the region of the exit window of the system. That is, for the best view of the display, the eyes must be fairly close to the optical axis of the system, and they must be at the proper distance. Deviations from the correct position result in distortions, blurring, and, ultimately, loss of view. A variety of approaches are under investigation that may improve this situation, including the use of special mirrors.

The depth of field in a visual simulation is usually limited by the optical characteristics of pick-up tubes and available light levels. Objects at a specific visual distance (an optimum distance is approximately 1500 ft.) may be in sharp focus, whereas objects nearer and further away may be out of focus. Whereas in the real world a pilot can alter his accommodation to bring closer and more distant objects into sharp focus, there is no way in which he can improve the sharpness of objects on a flat display that are not already in focus. The problem is the same for television monitors and projection systems. It can probably be improved by the development of more sensitive pick-up tubes and the use of higher levels of illumination, which will permit the use of smaller apertures (Smith, 1969).

Spatial resolution may be greatly reduced by losses in visibility that accompany fog and rain. Techniques have been developed to simulate such losses in visibility on television displays. The loss in visibility is introduced electronically. Some of the systems employed are relatively primitive while others are reasonably accurate and take into account the appropriate alteration of visibility as a function of azimuth and elevation. Another form of hazard to visibility is the accumulation of bugs on an aircraft wind-screen. This problem has been identified as a contributing factor in at least one midair collision. To date, there is no known effort to simulate this kind of effect, but it would be possible to do so.

<u>Visual Movement</u>.

With movement of an aircraft in space, an observer viewing objects outside sees a continuous change in perspective within the visual field along with changes in the relative size of the images of objects in

the field as their distance varies. Such a display provides a rich complex of cues, which afford continuous information as to the velocity of the aircraft. During landing and other maneuvers, the pilot is aided in predicting the outcome to be expected for various control inputs by means of the visual feedback he obtains. Within limits, the larger the visual field, the more easily such information can be interpreted. Limits are imposed by the limits of peripheral vision and the decline in spatial resolution capability with retinal eccentricity as well as the decline in sensitivity to relative movement in the visual field. As mentioned above, the larger the visual field, the larger the range over which the observer can scan for information and the larger the pattern of relative movement for any specific point of fixation.

Information derived from relative visual motion does not depend significantly upon the luminance distribution within the scene observed as long as there is sufficient illumination for the discrimination of different spatial elements within the field. The fineness of spatial resolution may be of some significance, but for increases in fineness of resolution beyond that now available in simulators, increased information would probably not be very great. Color can hardly be expected to add a great deal to the interpretation of visual motion patterns except insofar as it improves the identification of objects seen and hence improves estimates of their relative size and distance.

The most significant aspect of a visual motion pattern is the precise timing of the changes, particularly as these relate to control manipulations introduced by the pilot (Barnes,1970). In flight, such relations provide extremely important information as to the nature of the aircraft response. In flight, the visual motion pattern is always correct. There is no way in which the visual information can be distorted. This does not mean that misinterpretations cannot be made, but, with increased experience, misinterpretations will become less likely. Unfortunately, in a simulator, of all aspects of the visual scene, the timing of visual motion sequences is probably most difficult to present correctly. Physical and electronic models can be scaled accurately and the magnification afforded by pick-up and display components can be taken into account when models are used so that perspective views are essentially correct. The difficult task is somehow to create a proper sequence of visual movement. This depends on an accurate knowledge of how the aircraft will respond to controls under all conditions of flight, complete knowledge of the inertial characteristics of all moving elements in the pick-up system when a model is employed, and the ability to program aircraft characteristics accurately and to compensate for any deviation from idealized inertia-free response on the part of servos involved in the system. There is little evidence that these latter concerns have been given any very serious consideration by most of

the major users of simulators. The characteristics of servos are probably ignored or assumed to be taken care of by adjustments and trimming of the system which is done on the basis of subjective impressions of its accuracy.

The subjective impressions of expert pilots appear to be one of the major criteria in the evaluation of the adequacy of various aspects of simulation. These impressions are obtained in a careful and systematic fashion, but they remain subjective impressions, nonetheless. Interactions between the visual system, the kinesthetic system and the vestibular system are extremely important. Anyone who has worked with fixed-base simulators that include a visual display knows that visual motion in the absence of physical motion can be quite disturbing. Effects of viewing motion pictures of the outside world taken from aircraft or speeding cars are perhaps even more familiar to the general public. When one sensory system is stimulated actively and other systems, which would normally be stimulated at the same time, are not being stimulated, the effects may be quite disturbing. Perhaps more important, the response to stimulation that is being given may be distorted or differ from that which would occur under more natural circumstances. Thus, the subjective impressions of an experienced pilot may not be an ideal criterion for judging the accuracy or adequacy of a visual display in the absence of other cues upon which he has come to depend as complements of the visual inputs. There are ways in which objective quantitative determinations of the adequacy of visual motion simulations can be made, but these techniques have not been broadly applied. They will be discussed further in a succeeding section.

The dynamic equations employed for representation of an aircraft in the design of a simulator may provide a quite accurate description of the aircraft. On the other hand, they often include approximations. Even when they do not, the implementation of these equations in a simulation frequently will involve approximations. When higher terms are dropped and slight nonlinearities are ignored, the result may be a loss in realism. We have woefully little information on the response characteristics of the visual system for discrimination of movement on the basis of which to determine what sorts of approximation can be made without any loss in the realism of the display.

Designers have done the best they can in developing visual display systems. Theoretically, it would appear that the simulation of visual motion is substantially better than the simulation of actual physical motion of a simulator cockpit in even the most sophisticated mounting. Nevertheless, pilots appear to be much more critical of the visual simulation than of the physical movement simulation. They frequently criticize the "visuals" as incorrect, suggesting such specific criticisms as a sluggish response in the visual motion display to aileron control. It would be possible to obtain objective evidence as

to the accuracy of visual simulations by the use of motion pictures, which might record control inputs and visual display response simultaneously. National airlines has already undertaken some work with photographic evaluation of simulator fidelity. Evaluation of the films would be difficult, however. A simple initial approach might be to assess response to a variety of step inputs in order to determine the open-loop characteristics of the system. Such determinations could be made in aircraft as well as in the simulation of the aircraft. Some such evaluation must be made for further refinement of visual motion simulation.

MOTION SIMULATION

Motion simulation was an important component in some of the earliest LINK Trainers. These were relatively inexpensive devices operated by a pneumatic system. They permitted a limited amount of motion in pitch, roll and yaw with continuous change of heading. As the electronic systems and instrument display systems became more complex, there was a move toward fixed-base simulators that were very much more expensive but did not include any capability for the simulation of physical motion. Now, simulators with even more elaborate fidelity of cockpit layout and instrumentation are available, and motion capability has been restored. The cost of these modern simulators is orders of magnitude greater than the earliest simulators.

Motion capability has been restored because a great deal of evidence bolstered by virtually unanimous pilot opinion suggests that motion cues are extremely important (Brown, 1970). Motion cannot be simulated accurately within the confines of a simulator facility. The correct representation of all of the linear and angular components of acceleration for a given motion path can only be achieved by exact duplication of that motion path. An attempt has been made to solve this problem by duplicating the accelerations of the initiation of a motion pattern and then, gradually, at levels below the threshold for motion detection, decelerating and terminating the motion before the mechanical limits of the simulator are reached. This technique of "washing out" the motion appears to be quite successful. Since humans sense acceleration but not constant velocity, a fairly reasonable solution to the motion simulation problem can be achieved within practical space limitations.

The precise effect of a given motion pattern on a pilot may vary from one exposure to another, depending upon such factors as his posture in the seat, the position of his head and the nature of his attention at the onset of the motion. The precision with which a pilot can discriminate the detailed nature of a motion pattern is relatively crude compared with the precision of discrimination of visual motion. The accuracy of the simulation is probably, therefore,

more important in visual motion than in physical motion. It is possible, although no laboratory data on this point have been found, that with the addition of visual motion, the acceptable limits for a physical motion simulation are reduced and the physical motion simulation must be more accurate to be acceptable. Whether or not this is true will, of course, depend on the precise type of motion under consideration. It has been demonstrated that in helicopter simulations, the addition of physical vibration that was absolutely uncorrelated with vibrations observable in the visual display was quite acceptable and was judged very much more realistic than the same situation without the physical vibration. It is probable that the accuracy of correlation between visual and physical movement is much more important for controlled maneuvers, however. Under these circumstances, compatibility between physical motion simulations and visual display information has been shown to be quite important (Brown, 1960). An appropriate correlation of visual motion with physical motion is probably much more important when the visual motion is displayed in a simulation of the outside world than when visual cues to motion are presented by means of instrument displays. In any case, there is some evidence that pilots perform better in simulators when physical motion simulation is included than when it is not. There is also some evidence that when simulation of the visual world is added, the result is a reduction in performance rather than an improvement. This may result from some incompatibility between the physical and the visual motion simulations. The former is known to be a gross approximation of the real motion pattern. The latter has not been adequately evaluated.

It is certain that simulation of physical motion provides more than just an increased impression of realism. A NASA study reported in 1969 showed that the time spent by a pilot in observing the attitude indicator was significantly reduced when motion was added to a simulation. A good motion simulation does greatly enhance the impression of realism. It also provides important information concerning the effect of various pilot control inputs and it serves to influence the manner in which the pilot manipulates his controls. Abrupt, almost step inputs into the controls may occur in a fixed-base simulator. They are not used with motion simulation. Depending upon the range of movement available and the fidelity of the simulation, the pilot is immediately chastened for other than smooth, continuous control manipulations by a lurching movement of the simulator.

CRITERIA FOR EVALUATION OF SIMULATORS

Simulators are evaluated in a variety of ways. Some are primarily subjective, others are objective and quantitative. The nature of the evaluation process is, to some extent, dependent upon the purpose of the simulator. When a simulator is used to investigate the feasibility of certain design characteristics or as a basis for ascertaining whether

a pilot can fulfill the role which is planned for him in some vehicle still on the drawing boards, then there may be no way of ever knowing with assurance whether negative conclusions drawn from simulator work are valid. Where simulators are employed for training pilots to fly existing aircraft of known characteristics, there is an obvious ultimate criterion. To the extent that a pilot can learn to handle the aircraft in flight in less time than would have been required without simulator training, the simulator has been a success. Other criteria than the ultimate one are needed, however, for evaluation of progress of trainees. Some criteria must also be used for evaluating the simulator during various stages of its development. Subjective criteria, or statements of opinion, either of a pilot or of an FAA inspector as to pilot performance, represent the basis for most evaluation procedures. This is, after all, true for the evaluation of pilot performance in flight check-out as well. The most general question concerns how well the task of flying a simulator seems to duplicate that of flying the aircraft simulated. To an FAA inspector, the question may be one of how closely the simulator-trained student pilot can come to matching the performance of a pilot who has received all of his training in the aircraft after like amounts of experience. For research, design, and development work, some effort is usually made to obtain objective, quantitative measures of performance as well as subjective evaluations. Some of the problems associated with various types of simulator evaluation are considered in the following paragraphs.

<u>Quantitative Indices of Performance.</u>

<u>Characteristics of Flight</u>. The most critical maneuvers are take-off and landing, and landing is perhaps the more critical of the two. It is possible to obtain measurements of the pilot's control performance in a simulator to compare them with the control performance that would be expected in an actual flight. Some of the indices of flight performance that are often observed for landing maneuvers include rate of descent or sink rate in ft. per sec., the vertical component of acceleration, point of touch down, the glidepath slope, rate of lateral motion, the precision of longitudinal control and the overall coordination of flight. A measure that may be obtained for many of these indices in a single trial and for all of them in repeated trials is variability. Variability may reveal important effects when average values show no deviation between a simulator and the aircraft simulated. Variability may also provide a useful criterion of changes in pilot performance resulting from stress or fatigue.

It is possible to obtain direct measurements of the continuous motor performance of a pilot in the manipulation of controls from which a transfer function or frequency response characteristic for the pilot may be calculated. This sort of information is useful for the prediction of the maximum rate with which the pilot may be capable of responding to

various sorts of information inputs from direct view of the outside world or from the instrument panel. If the pilot transfer function were an invariant index of his performance, it would be exceedingly useful. Unfortunately, it has been demonstrated that a pilot transfer function may vary, depending on how it is measured and depending on the nature of the performance demanded of the pilot, as well as the simple day-to-day variability that occurs under similar circumstances. The use of pilot transfer functions is restricted almost entirely to research.

The rate of descent of a Boeing 727 at touch down is approximately 3 ft. per sec. in flight. In a simulation of the Boeing 727, the rate of descent is typically higher, sometimes by as much as a factor of two. Work on a simulation of the Concorde at the Ames Laboratories of NASA has shown that the sink-rate and vertical acceleration both tend to be higher in the simulator than in the aircraft. The sink-rate is approximately 2 ft. per sec. in the aircraft and 3 or 4 ft. per sec. in the simulator. Comparisons made by NASA of performance based on rate of descent and touch down point in simulators, where the simulation of the outside visual world is derived from a physical model on the one hand and is generated entirely electronically on the other, show no difference for these two situations. In general, the rate of descent in a simulator is greater than that which occurs in actual flight during a landing (Chase, 1967). The reason for this is unclear. Experienced pilots who know what the optimum rate of descent should be in an aircraft are able to fly a simulator so that the landing maneuver conforms in such dimensions as rate of descent with values which occur during actual flight. They do this by flying the simulator in a way which seems to them somewhat different than the way they would normally fly the aircraft, however. An over-emphasis on the importance of matching the computer's physical characteristics of flight in a simulator to those which are norms for the aircraft would therefore be most inappropriate. It would undoubtedly lead to an increase in the artificiality of the simulator situation.

Differences in the previously mentioned quantitative indices between a simulator and the aircraft simulated do not necessarily mean that the simulator is unsatisfactory. If the ultimate criterion is met and the pilot can learn to fly the aircraft by practicing in the simulator, then the simulator is obviously useful. It is important to recognize in our consideration of quantitative indices that those obtained from a simulator need not match those obtained in flight. In fact, if a pilot must consciously alter his normal behavior in order to match such values as rate of descent in a simulated landing to that which he knows to be the norm in flight, then it is probable that the more closely the overall pattern of quantitative indices match those in flight, the less natural and hence perhaps the less satisfactory is the pilot's simulator experience.

It would, of course, represent an ideal situation if predictions could be made accurately on the basis of simulator performance of various quantitative indices of flight characteristics in an aircraft. Our simulators have not yet evolved to the point where this is possible, however. Quantitative indices are useful, perhaps particularly from the standpoint of assessing variability of pilot behavior and deviation of the simulator from flight conditions. An effort should be made to improve the simulator on the basis of such criteria.

Physiological Measures. A variety of measurements can be made of the physiological state of a pilot in an aircraft or in a simulator. Such measurements provide objective and quantitative values. Variables frequently recorded include the electrocardiogram, respiration, and skin conductance. These variables are probably of some value in providing information as to the pilot's health and well-being, his general level of arousal, and perhaps something of his physiological response to emergency situations, prolonged and fatiguing activity and other external variables. Inferences as to a pilot's psychological state or the maximum possible efficiency of his performance from these measures are exceedingly dangerous, however. Such measurements are of great interest experimentally in research contexts but as yet are of only limited relevance for assessing pilot performance during routine training operations.

Subjective Criteria.

At the present time, subjective criteria probably play the most important role in the evaluation of simulators. After a simulator has been designed and constructed, matching the known characteristics of the simulated aircraft as closely as the present state of the art will permit, it is evaluated by recourse to the opinions of pilots experienced in flying the aircraft. Evaluation may be highly systematic, involving a series of selected maneuvers chosen to demonstrate, as broadly as possible, the "flight" characteristics of the device. The procedure may be improved somewhat by involving more pilots representing a broader range of flight experience and permitting the determination of a somewhat more representative reflection of the population of pilots as a whole.

A variation of this subjective procedure, which may be regarded as a refinement, involves the use of an experienced judge who evaluates the performance of pilots who fly the simulator. The evaluation is performed much as an FAA inspector assesses the adequacy of a pilot's performance in flight for an FAA check-out. A standardized sequence of maneuvers and tasks must be undertaken by the pilot and his performance of these provides a basis for the inspector's judgment of the pilot. An inspector with extensive experience may be able to provide an evaluation of a simulator in terms of the way in which a

reasonably large sample of pilots is able to perform in the simulator compared with the way in which a sample would perform in the aircraft itself.

The utilization of standard tasks, an adequately large number of pilots, and the judgment of a qualified inspector provide a basis for the determination of fairly reliable and probably valid assessments of simulators with respect to their adequacy for the representation of specific aircraft.

The difficulties encountered in any effort to obtain evaluations of simulators, particularly of a quantitative nature, have resulted in considerable reliance on "face" validity. Any characteristic of a simulation that in any way makes it seem more similar to the aircraft may be said to enhance its face validity. Characteristics of a simulator which contribute to face validity very often contribute to actual validity, or the real effectiveness of a simulator as a testing or a training device. There is no assurance that improvements in face validity will also improve actual validity, however. If we were possessed of detailed knowledge as to just what aspects of available information a pilot is dependent upon for aircraft control, it might be possible to evaluate suggested "improvements" in simulator design in terms of how much they might contribute to actual improvement in performance. Unfortunately, we do not now have sufficient information to do this. In the case of training simulators, we must depend on the ultimate criterion of how effectively training can be accomplished with the simulator measured in terms of performance in the aircraft. It is always possible that some "refinement" in a simulator, which may superficially seem to improve its similarity to the aircraft simulated will actually reduce its similarity with respect to the important cues on which performance must be based.

<u>Transfer of Training</u>.

From the record of commercial aviation, it is well established that simulators provide an effective means of reducing the cost of pilot training. At the time the American Airlines new simulator training program was inaugurated in 1966, pilots required an average of approximately twenty hours of in-flight training to transition to a new aircraft. As the simulation program progressed, this requirement was gradually reduced by a factor of five to ten for various aircraft types flown by American (Moran, 1971b). In one of the most recent types adopted, the DC-10, average time in flight for both training and check-out has been reduced to two hours and eleven minutes. One pilot required only one hour and nineteen minutes of flight training and check-out in the DC-10. Although with simulators, pilots require approximately the same number of hours in training, the total time required is actually reduced by reason of the greater availability

of simulators and the elimination of much of the preparation time. The safety associated with elimination of much of the in-flight training time, the release of aircraft for revenue flights, and decreased cost of operating a simulator rather than an aircraft for training all add up to a highly positive evaluation of simulators with a quantitative index measured in dollars, which is not likely to be misunderstood or ignored.

It is obvious that there is substantial positive transfer of training from a simulator to an aircraft. Some concern has been expressed, however, over the fact that transfer in the other direction is not particularly good. There are no precise quantitative measurements of performance, but it has been suggested that transfer from simulator to aircraft seems to be of the order of 95%, whereas transfer from aircraft to simulator is only 5%. Pilots are regularly required to undergo recurrent training. They must report to the American Airlines Flight Academy for refresher training on the simulator at regular intervals. Frequently, they encounter difficulty in flying the simulator after extensive experience in the aircraft. Two somewhat different explanations for this asymmetry of transfer have been suggested. Some of those involved in the simulation program believe that the problem is associated with the reduced set of cues available in the simulator. The cues are adequate to learn to fly a specific aircraft type, but they are incomplete and they may be slightly in error. When a pilot transitions from the simulator to the aircraft, he is able to perform adequately with the cues which were available to him in the simulator, now available in more refined form, and he is also provided with additional cues which were not available in simulation. After extensive flight experience, his sensitivity to various patterns of cues and their interaction becomes highly refined. When he returns to the simulator for recurrent training, he is faced with a reduced set of cues which may also be inaccurately interrelated compared to those to which he has become accustomed in the aircraft. He thus encounters some difficulty. It has been suggested that differences in handling characteristics of individual aircraft may further complicate this situation. A pilot flying an aircraft is always able to integrate the pattern of stimulation to his vestibular system with changes in the outside visual world regardless of the handling characteristics of the aircraft, but he will probably not be as successful in accomplishing this integration with the reduced visual cues available to him in the simulator.

A second proposed explanation for the asymmetrical transfer between aircraft and simulators, based on experience with the American Airlines simulators, attributes the problem primarily to the nature of the simulation of the visual world. It has been suggested that the equations employed in that part of the system which controls movement of the television camera over the scale model are either in error or too approximate. Pilots frequently report that the outside visual simulation

seems to respond sluggishly, particularly with respect to lateral control. Some pilots have adopted a policy of flying instruments down to an altitude of approximately 50 feet in order to avoid confusion that might be engendered by an inaccurate display of the outside visual world. Finding that pilot performance is improved by motion simulation but is better on instruments than on the outside visual simulation would seem to support the contention that the visual simulation is faulty. It would be premature to accept this conclusion without a more probing evaluation of the problem, however. Suffice it to say that, although simulators are different and will remain different from aircraft, they appear to have proven their worth for training purposes as measured in savings of time and money required for a qualification of pilots in new aircraft types.

RECOMMENDATIONS FOR FURTHER RESEARCH

Parameters of the Visual Simulation.

Simulation of the visual world for aircraft flight simulators involves the presentation of spatial patterns of varying brightness and color that change in a manner corresponding to the simulated conditions of flight. Efforts have been directed toward the achievement of realistic degrees of spatial resolution, a correct rendering of luminance and color characteristics, the provision of an adequate field of view, as much depth of field in a flat plane presentation as can readily be achieved and, perhaps most important, a continuous change in perspective to match the relative motion of the aircraft with respect to the outside world. Most of these variables are subject to wide ranges of variation in actual flight. On the other hand, visual motion, or the inference of motion based on changing perspective in the visual world, is rigidly determined by the specific motion time history of the aircraft. For the pilot, visual motion is exactly correlated with the physical motion that stimulates his vestibular, kinesthetic and tactual sensory systems. The feedback provided to the pilot by motion as sensed in any sensory dimension is an important element in his continuous control of aircraft flight. Our survey of simulators suggests that perhaps too much concern has been devoted to such variables as spatial resolution, color, and luminance and too little to the fidelity of visual motion in simulation displays. Visual motion simulation may be based on fairly accurate equations of motion but the implementation of these equations may involve approximations and simplifications. In addition, the inertial characteristics of mechanical elements in the simulation system may not be taken into account.

It would be highly desirable to attempt to obtain a quantitative measure of the fidelity of visual motion simulation. One approach to the task is the use of motion picture film to record instrument displays, the simulation of the outside visual world and control

manipulations simultaneously. This would permit a determination of the precise relations between changes in perspective of the outside visual world, changes in instrument displays and the control manipulations which induced these changes. A first step in such an evaluation should probably involve the use of step-function inputs to the controls with a careful determination of the nature of the response both in the aircraft and in the simulation of the aircraft. Such measurements might not permit complete prediction of the continuous closed-loop control sequence in specific maneuvers, but it represents a reasonable starting place. If it is not the most important characteristic of the visual display, visual motion is, without question, one of the most important aspects. More energy should be devoted to this parameter than has been given it heretofore.

In-flight measurements should make it possible to achieve a highly accurate portrayal of visual motion in a simulator, particularly with an electronically-generated display where no problems associated with mechanical inertia are encountered. With a display in which the visual motion cues are known to be correct, it would be possible to evaluate the significance of such parameters as spatial resolution, luminance, color, depth of field and field of view by the process of degrading these various dimensions selectively and individually. The accuracy of the visual motion simulation may also be degraded to determine just how important it is in a simulation. It is much easier to evaluate the results of such an investigation with a knowledge of how much the various parameters deviate from the conditions encountered in actual flight.

Information concerning the relative precision necessary for various dimensions of a visual simulation will be extremely useful in the design of both physical and electronic systems. The relative importance of visual resolution and spatial detail for satisfactory visual simulation is of particular concern in the design of electronically-generated visual displays. The presentation of fine detail is presently not a practical possibility with such devices. If it can be shown that this dimension is of lesser importance than an accurate simulation of visual motion, electronically-generated displays with their several advantages might find readier acceptance in certain areas where they are not presently used. If spatial resolution is shown to be of great importance, then more effort should be devoted to high resolution, laser displays (Stone et al., 1969).

New Display Types.

Some effort should be given to a continuing evaluation of new types of visual displays. Some of the possibilities include systems that employ various sources for the visual display in a single installation. For example, it might prove profitable to employ electronically-generated displays with a conventional raster-type display on a television monitor

for some segments of flight and somewhat more schematic presentations employing line elements directly traced on the scope face (calligraphic displays) for other aspects of the presentation (Sutherland, 1970). It has also been suggested that combinations of a film presentation for cross-country flight with the use of scale models of airports for take-off and landing might prove useful.

Pilot Performance.

An extremely important aspect of the use of simulators is the development of appropriate methods of assessing how satisfactorily pilots perform. As discussed above, present methods are primarily subjective and attempting to develop somewhat more objective procedures is important. In our concern for evaluating how well pilots can perform various maneuvers, we sometimes overlook the importance of another question. That is, precisely how pilots perform. It is possible to question a pilot as to the procedures he employs in performing maneuvers with respect to the information he needs at various times and the instruments or other sources from which he obtains it. He may provide a fairly detailed account of his performance, but there is no guarantee that his introspective account is accurate. It would be of great value to extend work which has been undertaken on the determination of exactly what procedures a pilot does employ in controlling an aircraft. With recently developed equipment, it has become possible to obtain a continuous record of exactly what the pilot is looking at from moment to moment on the instrument panel and outside the aircraft (Weir and Klein, 1969). Such records are extremely useful in assessing the detailed nature of pilot control and the type of information to which a pilot responds. There is preliminary evidence to the effect that this changes with increasing proficiency. Such records therefore afford a possible basis for assessing a pilot trainee's progress in learning to fly or in transitioning to a new aircraft type.

A further value of such records lies in the fact that they provide a basis for ascertaining the importance of a simulation of the outside visual world. One can obtain a measure of the relative amount of time spent in observing the world outside the aircraft as compared to the instrument display in various conditions of flight: take-off, cross-country, low altitude, and landing. Outside visual reference is undoubtedly more important under some circumstances than others. The nature of simulations to be used for training in various conditions may be altered accordingly.

As suggested earlier, it would probably be useful to extend investigations of pilot performance in terms of the continuous control motions of the pilot employed for the execution of various maneuvers. A time history of control movements provides a basis for determining the power spectral density characteristics of the pilot. It would be

useful to know just how such an index may differ for a novice as compared with an experienced pilot and how such an index may vary from one condition of flight or from one aircraft to another. In addition, such an index might be useful in assessing the effects of fatigue or of selective reduction of information provided to the pilot.

Many investigations have been carried out to determine the relative importance of various items of information by gradually degrading certain dimensions of the overall information display available. Many of these investigations have not been successful by reason of the fact that there is not a corresponding gradual degeneration of pilot performance. Pilots continue to perform quite satisfactorily up to some point where there may be an abrupt breakdown in performance. The implication is that the pilots are able to compensate within fairly wide limits. Their ultimate breakdown results when a limit of compensation is reached and breakdown cannot be attributed to the specific item of information which is eliminated just prior to breakdown.

It has been suggested that the power spectral density of pilot performance or the transfer function for the pilot in the control loop might provide a more continuous indication of changes in the pilot's performance as information inputs are degraded. Another suggestion is that various physiological indices may provide information as to the development of increasing stress on the pilot as he is forced to compensate in the face of reduced information. This possibility has been investigated in a number of laboratories for many years. Some additional work in simulators might prove interesting, however. Specific measures frequently obtained include heart rate, the complete electrocardiogram, respiratory rate, psychogalvanic reflex and skin resistance at various locations.

Pilot Opinion.

Evaluation of the adequacy of flight simulators will continue to depend to an important extent upon pilot opinion. It is therefore most important to assure that the techniques employed for sampling pilot opinion are the best available. It would probably be useful to employ somewhat more systematized procedures than those now used, to increase the number of standard tasks which provide a basis for opinion questionnaires, and to seek the advice of authorities in the field of opinion sampling.

The Simulation of Physical Movement.

As mentioned above, the movement dimension has been recognized as an extremely important one in flight simulation. It is important to consider it in conjunction with visual simulation procedures by reason of the important correlation between visual movement and

physical movement in the real world. Additional research is needed on thresholds for movement detection under various situations in order to improve motion simulation and the use of washout techniques required by the severe physical limits imposed by most simulator installations.

Partial Simulations.

Additional research is needed on the extent to which successful training can be achieved with the use of part-task simulations. A completely comprehensive simulation can only be used for one aspect of a task at a time, although it may have the capability of being used for all. In addition, it is extremely expensive. Only one trainee can use it at a time and therefore others must wait for access to the device. A larger number of part-task simulators could be acquired for the cost of one complete simulation and might permit the training of a larger number of individuals simultaneously.

The value of elaborate simulators for pilot training has been demonstrated conclusively. It is now desirable to undertake an investigation of how training procedures can be accomplished less expensively and more efficiently by simplifying simulators whenever this can be done. It should be possible to reduce the cost of simulation facilities,or at least improve their efficiency, by permitting them to provide training for more individuals without loss of training effectiveness.

SIMULATION RESEARCH: FACILITIES AND PERSONNEL

The facilities required for simulation research are in general too elaborate and too expensive for work to be done in university laboratories. The optimum locations would appear to be in government laboratories, particularly those of NASA, and in the facilities of the commercial airlines. Unfortunately, the latter facilities are so burdened with training requirements that little, if any, time is available for continuing research projects. Many of these facilities are now operating for extended hours, seven days a week, and have only minimum time for regular routine maintenance work. The commercial facilities also lack the flexibility which is desirable for research applications. It would appear desirable to carry out research involving new types of display primarily in government laboratories while perhaps attempting to do some research on training procedures and techniques within the commercial facilities. Qualified investigators include psychologists and engineers in government agencies such as NASA and the FAA as well as their counterparts with airframe manufacturers and the commercial airline companies. Relatively few qualified investigators with extensive experience in simulation work are found on university faculties.

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APPENDIX

Working Group 34 - Preliminary Reports

A. LANGLEY RESEARCH CENTER, LANGLEY FIELD, VIRGINIA

1. The Langley Research Center was visited on July 12, 1971 by Leo Fox, NASA Headquarters, William Benson, Executive Secretary of the NAS-NRC Committee on Vision, and J. L. Brown Chairman of the Working Group and Staff Advisor to the Vision Committee. A discussion was held with Perry Graves, Director of the Electronics Division and James Whitten, Associate Director. The general purpose of the Working Group was outlined by the visitors, and Graves summarized the current efforts at Langley. This discussion was followed by a visit to a number of installations in the laboratory.

2. One of the more interesting installations is a simulator developed by Northrop Aviation Company, the Differential Maneuvering Simulator (DMS). It consists of two 40 ft. spheres in which the simulation cockpits of F4 aircraft are located. Limited amounts of motion of these cockpits are possible. With the aid of projectors the insides of the spheres are illuminated with a ground terrain, horizon, and sky. These components of the display can be moved by means of the gimbal mounting system of projectors such that turns, rolls, banks, and other maneuvers are accompanied by appropriate relative motion of these elements in the visual world. Since there is no "flow" of the ground terrain beneath the aircraft, speed of the sircraft is not indicated by relative motion of objects on the ground; only pitch, roll, and yaw are represented visually. The primary purpose of the simulator is to investigate problems which may involve the relative maneuvers of two aircraft. A picture of an aircraft is displayed within each hemisphere to represent the aircraft under control of the operator in the other hemisphere. The aspect from which this photograph is viewed, its size, and its position and motion over the surface of the hemisphere accord with the relative motion paths of the two maneuvering aircraft. Thus, an operator in one hemisphere "sees" the aircraft that is controlled in the other hemisphere. Its movements are realistic with respect to those simulated by his own aircraft, and its altitude, size, and relative motion vary in accordance with the way he is operating his aircraft relative to the movements of the other aircraft, but there is no attempt to change sun-angle to correspond with changes in attitude. The simulation is suitable neither for landing maneuvers nor for low altitude terrain clearance studies. However,

it does provide a highly realistic simulation of the differential maneuverings of two aircraft. Its primary value probably rests with the study of air-to-air weaponry systems and air-to-air maneuvers. An application that was not mentioned but that may have some importance is collision avoidance. Conceivably, the simulators could be programmed to represent a variety of aircraft, and emergency potential collision situations could be simulated, affording a study of pilot responses, a definition of those situations from which recovery or collision avoidance could be accomplished, and some quantification of the relative difficulty of avoidance of potential collisions that arise for various relative courses and attitudes of the aircraft involved. Servo controls of the projectors that are utilized in the simulation appear to be extremely smooth. The simulation seemed quite realistic, and, in the opinion of pilots who have worked with it, it is exceptionally good. Its limitation is that it is useful only for air-to-air work and was primarily designed for air-to-air combat maneuvers.

3. It is clear that considerable effort has been made at Langley to utilize equipment originally developed for other purposes in connection with new problems, for the old moon landing simulator that was developed at Ames has been converted for the study of short takeoff and landing (STOL) problems. The moonscape of one section of the wall has been replaced by an airport model. There is a severe limitation on the range that may be covered, but it is not serious for the STOL application.

4. During visits to the various simulator facilities, the general area of visual simulation was discussed, primarily with Whitten. The significant qualitative difference between simulators and the real world may, in his opinion, result from lack of adequate detail in simulators. In addition to the reported subjective differences between simulators and the real thing, it is also notable that pilot performance differs quantitatively in simulators from performance in aircraft. One useful index in landing is rate of descent at touch down, and there are considerable data available on this for a variety of aircraft under a variety of conditions. The variability of the data is also known. Although a pilot will land a 747 with a rate of descent of approximately 3 ft/sec, his rate of descent in a simulation will be somewhat greater. Study of the situation is complicated by the fact that pilots can fly simulators so that the rate of descent will be about the same as that which would be obtained in the real aircraft, but they do so by using artificial cues so that their results correspond to what they know are typical values generated in a real landing.

Some defect in a film strip or a reference point on a display may be employed. Precautions must be taken to prevent pilots from using such cues when studying the adequacy of simulators.

5. Arthur Vogeley presented a brief discussion of the significance of "visual streaming," the flow of objects in the visual field, outward in all directions from some point of origin in a frontal plane as that point is approached at high speed. Such cues provided by objects on the ground are undoubtedly important in flight at low altitudes and particularly during landing. Efforts are presently being made to develop a display that provides a horizontal line pattern that moves downward on a CRT at a rate that varies properly with the altitude of an aircraft as it comes in to land. The display in its present configuration includes no possibility for the control of roll or yaw. Control in pitch is possible with the vertical position control of the CRT. It is noped that some work may be accomplished with this device in checking the significance of the angle of view. Vogeley suggests that there may be some "inherent" response system available in the organism that responds directly to "visual streaming" as a cue. The streaming pattern would vary for different approach angles, and the significance of the streaming pattern might be influenced by background factors such as open plains, high mountains, harbors, and city illumination at various elevations about the plain of the runway. Work that may be significant in understanding possible relations between background elements and the visual streaming cues has been reported by Conrad Kraft of The Boeing Company. At the present time, no quantitative work has been accomplished on the visual streaming cue, and future plans have not yet been firmly established.

6. The General Electric Corporation in Syracuse has developed a highly realistic computer-generated display that goes well beyond the highly schematic computer-generated displays that are now available and a computer-generated demonstration film was shown to the visitors. This film employs 24 edges for the depiction of an aircraft, terrain, and an airport. The computer-generated display provides for complete control and either in-aircraft or on-ground or in-other-aircraft perspective of the situation. Color, luminance, and spatial factors are independently variable. Complete 360^{o} control of motion about any axis is possible, as well as complete freedom of control of relative speeds. Nonlinearities and servo deadzones that might be implicated in the lack of realism encountered in certain mechanical simulators can be simulated with the computer-generated display for their precise study.

Spatial resolution is limited by the number of lines or edges employed. The 24-edge procedure that was used in the manufacture of the film would be equivalent to approximately 1200 edges in a real-time simulation. The device may thus be considerably short of a practical real-time prototype. Another limitation is the angle of view afforded by a CRT. This limitation can be offset to a degree by the use of a projection screen, although such a procedure would be much more expensive and would result in some apparent loss of resolution. ((Note: A contact for additional information on the computer-generated display is C. H. Ide, Manager, Simulation and Digital Systems Engineering, General Electric Corporation, Binghamton, New York, (607) 729-2511.)) From the standpoint of flexibility, the computer-generated display and its capabilities as these are forecast in the motion picture that General Electric has prepared would seem to offer the greatest latitude for experimentation and for control of the variables involved in the flight simulation problem. However, it may not be possible, at least in the near future, for this technique to produce a display of sufficient resolution in real time. The matter will be pursued further with representatives of the General Electric Company.

7. A study peripherally related to the problem of visual simulation was described briefly. This study tests an observer's ability to respond correctly to the direction of motion of an instrument pointer when the instrument is not viewed directly in foveal vision. Detectability of movement is being determined for several eccentricities of the display.

B. AMES RESEARCH CENTER, MOUNTAIN VIEW, CALIFORNIA

Brown visited the Ames Research Center on July 13-14, 1971. It was not possible for Fox and Benson to make the trip.

1. <u>Installations</u>

a. A tour was given of some of the facilities available at Ames. First examined was the large REDIFON simulator, which consists of a model landscape with airfield in a vertical plane over which a television camera may be moved and turned to correspond to motions simulated in the aircraft cockpit installation. The original incandescent illumination has been replaced by fluorescent which results in much more efficient lighting and cooler ambient temperature. Realism is achieved with this

installation by starting a landing operation with the pick-up camera in a tub, inside of which a horizon is painted. The result is a reasonable simulation of high altitude flight with no detail visible on the ground below. The aircraft is brought down so that the model comes into view by electronically introducing a "fog" while the tub is removed and the television pick-up is appropriately positioned. The fog is then gradually dissipated, revealing the model and the aircraft runway in correct relation to aircraft position. At present, the function that permits simulation of fog is equivalent to a single flat plane of degradation of visibility. Therefore, visibility is greater off to each side than it is straight ahead. Appropriate corrections will be made in the simulation to render this effect more realistic.

b. A flight simulator is available for studying advanced aircraft, particularly under circumstances where high lateral accelerations and decelerations may occur. In order to create appropriate motion effects, a 100 ft. track provides a base for the simulator housing and lateral motions along this 100 ft. range are possible. The maximum lateral acceleration is 12 ft/sec^2 and the maximum velocity, 17 ft/sec with a frequency response of 1 Hz. at a 30° phase lag. Vertical movements of $\pm$5 ft. and longitudinal movements of $\pm$4 ft. are also possible at 12 ft/sec^2 and 10 ft/sec^2, respectively. Angular displacements of $\pm 45^\circ$ in roll, 22½$^\circ$ in pitch, and 30° in yaw can be achieved. The visual simulation in this device is currently displayed on CRT monitor viewed through a large collimating lens. The control system for operation of the device was dysfunctional during the visit, so no demonstration was possible. Visual resolution on the monitor-lens system is estimated to be about 7$'$. A simulation of the Concorde was thought to be very good by the French pilots who tested it. There is much concern with possible lateral instabilities in this aircraft. John Dusterberry stated that both sink rate and vertical acceleration tend to be higher on this simulator than in actual flight. Although sink rates in aircraft may be 2 ft/sec, the rates in the simulator are 3 to 4 ft/sec. Dusterberry did not believe that this had anything to do with the servo control systems. He felt that it might be related to visual resolution. In any case, something seems "unreal" to the pilots at low altitudes.

c. A General Precision Systems (GPS) Simulator, made in England, as is the REDIFON, was examined next. GPS has recently been bought out by REDIFON. This simulator employs a very wide moving belt on which is mounted a three-dimensional landscape with houses, shrubbery, runways, and roads. Large objects such as hills and mountains present a problem when the substrate of the belt is flexed as it goes around the pulleys. The television pick-up camera can move laterally and vertically as well as about axes of rotation, while longitudinal travel is introduced by belt motion. A similar device is under development by Link Aviation. The cost of the Link device is approximately $1,000,000, while the GPS device is approximately $700,000. A new Vidicon tube has been installed in this device to improve resolution, and the visual display is further enhanced by the use of peaking circuits. Wendell Chase has recently been concerned with color measurement and a specification of colors available in the original scene and as reproduced on a color television screen remotely with this system. Both a remote projection screen and direct view of the tube through a collimating system have been employed. Resolution is better with the tube than with the projection screen. The projection screen is quite heavy and costs approximately $75,000 as compared to the $5,000-$7,000 that the tube system costs. Some problems have been encountered in the matching of the camera to the scale on both the REDIFON and the GPS devices. It would be possible to do 360° rotations with a gimbal-mounted camera and slip rings, but the width of the belt poses limitations for complete freedom of aircraft maneuvering.

d. A study of the detectability of flashing lights is being conducted by Mary Connors and a demonstration of the study was observed. An old facility that was originally designed for testing discrimination of star patterns is employed. A static pattern of 55 tiny lights is presented against which 24 targets must be detected. Targets flash on and off for a brief interval and are of a different color than the static lights. Studies are now being conducted on discriminability of red and blue test lights.

2. Presentations

A series of presentations was organized by various members of the Ames staff.

a. First was a presentation by Maurice White, Chief, Flight Systems Research Branch, entitled "Visual Display Requirements in the Simulation of Flight Maneuvers." White mentioned that there is a committee for simulator design that is concerned with the variables of both motion and vision in such design. A number of factors dictate the necessity for a wide field of view in simulators. For example, the STOL problem involves a circular landing pattern. REDIFON has developed a new mirror for this problem. Plans have been developed for coordination of U. S. efforts with British activities in simulator development. In the Federal Aviation Administration (FAA) Ferrarese and Noltmeier are concerned with coordination of various simulator efforts. It is estimated that the mechanical limit of vertical motion for an appropriate simulator will have to be approximately 60 ft. At present, the height control test apparatus permits vertical displacement of 100 ft. with an acceleration of $\pm 0.7g$ and velocities of up to 18 ft/sec with a frequency response of 1.5 Hz. at 30° phase lag.

Currently, pilots can be checked out on a number of maneuvers in simulators. A total of 16 maneuvers must be performed in aircraft, however. The reason for the selection of these 16 maneuvers by FAA is not entirely clear. Nine of them deal with asymmetrical thrust, loss of one or more engines on one side of the aircraft, and, hence, severe motion effects. These are difficult to simulate but involve a certain amount of hazard when they are performed in aircraft. Even though the engine "failure" is simulated in the aircraft simply by throttling back so that recovery of the engine is theoretically possible should an emergency arise, some accidents have occurred while simulating these maneuvers.

Link Aviation has devised a simulator that is capable of motion of four feet in translation in each of three dimensions. One of these is operated by American Airlines at Fort Worth, Texas. The Director of Training Equipment Development there is Robert Houston This simulation is extremely good for such things as engine failure. A study will be conducted which will emphasize nine maneuvers of those involved in aircraft pilot checkout. Some study of the transfer of training to actual flight in the 747 will be attempted.

b. The second presentation was by Wendell Chase, accompanied by M. Sadoff. He described briefly an old Dalto System narrow belt landing simulation device. Much improvement

has occurred relative to this device over the last five years. However, Sadoff interjected that there is no objective evidence that the improvements that have been made have resulted in the valid improvement of the simulation as a training or testing device. Some attempts have been made to compare a TV monitor and a collimating lens to a projection system. The depth of field functions are the same for projection and for the monitor. They are best at approximately 1500 ft. The projection system tends to flatten out the resolution function. There is some preliminary evidence that a slight degradation in resolution has no effect on the value of a simulation for training and testing. Sink rates are invariably higher on a simulation than in actual flight and are higher with the projector than with the TV monitor. The sink rates are approximately doubled in simulation. This difference holds when feedback as to actual sink rates is not given. When feedback is provided, research pilots can approximate the normal function of rate of descent as this changes during the course of a landing. Pilots prefer the TV monitor over the projection screen, which accords with the closer value of sink rate for the monitor to that in actual flight, and prefer color over black and white presentation. To date, there have been no known quantitative tests of the advantages of color, so it is not known whether this preference is reflected in performance. Considerable speculation has been directed toward the issue of why there are differences between simulators and flight. Motion is probably one important factor. It is impossible in any simulator to duplicate the motion time histories of actual flight with complete accuracy. All components cannot be the same without an actual duplication of the motion. Another factor is the field of view. In general, the field of view is relatively more limited in a simulator than it is in actual flight. This factor is something that will be studied extensively by Mary Connors. Another factor is the depth of focus of the presentation in the simulator as compared with the real world. Because of limitations in the optics of a simulation system, much of the picture is out of focus and cannot be brought into focus by the observer. In the real world, accommodation can be changed to bring any aspect of the visual presentation into focus at the volition of the observer. A fourth factor is limitation in resolution of detail. The human eye is capable of resolving elements of visual detail down to one minute of arc or less in the real world. The maximum resolution available in most simulations is estimated to be about 6 or 7 minutes of arc.

c. Mary Connors presented a brief resume of her experimental program for studying field of view. The field extends from 190° to 220° horizontally in most aircraft. It may be as little as 26° vertically. She has done some background research on the threshold for detection of movement in various regions of the retina and finds that the fovea is more sensitive to movement by a factor of approximately 20 than at a location 8°-10° away from the fovea. That is to say, movement at a lower rate and over a shorter distance can be detected in the fovea than is the case in the periphery. There is some confusion on this point in the thinking of many who are not expert in visual science and even in the thinking of some who are. There is a prevalent notion to the effect that the periphery is much more sensitive to motion than the central visual region. This confusion has arisen because the periphery is much more sensitive to motion than it is to stationary spatial elements. Things that attract attention in the periphery are therefore very much more often moving. Relative to discrimination of stationary patterns, then, the periphery is very much more sensitive to motion. Relative to the motion detection sensitivity of the fovea, however, the periphery is quite insensitive. The fine sensitivity of the fovea to motion is perhaps overshadowed by its excellent capability for the discrimination of static spatial detail. In addition, the motion of objects in the fovea is not important for their detection since they are already in full foveal view. Movement is thus more important in peripheral vision than it is in central vision because it is so often a basis for detection.

The experiment will investigate horizontal fields of view from a maximum of 220° down to a minimum of 4°. Studies of performance will be conducted, perceptual indices will be measured, and a variety of physiological variables will also be measured in order to test for possible differences in the stress-value of the situation with different fields of view. Earlier studies have been reviewed and these show some differences. Gracie has reported some effect of reduction of the horizontal field when it reaches 22°. Others have found no effect until the field is narrowed down to $\leq 15^{\circ}$. Hasbrook, at CAMI, has carried a study of the effect of horizontal field of view down to 4°. He attributes the severe loss found with very small fields of view to the elimination of certain external referents, such as points that are visible on one's own aircraft. A stationary reference provides an important element in many visual discriminations, and it is particularly important in the discrimination of motion. Sensitivity to

motion is much greater when a stable reference point is present in either the fovea or the periphery.

The extent of the field of view may be more critical at night than it is during daylight because of the restrictions night visibility imposes. Among indices that have been employed in assessing performance of pilots during aircraft landings, touch down point has been commonly used. This is believed to be an inadequate measure by itself. In Connors' study, measurements will be made of sink rate, lateral rate, glide slope, longitudinal control, and overall coordination as well as touch down point. Physiological measures will include the electrocardiogram and respiration. It is tentatively planned to have the work done by an outside contractor such as the FAA Laboratory at Oklahoma City, Cornell Aeronautical Laboratory, or the University of Illinois. Ames now has a contract with the Visibility Laboratory, Scripps Institution of Oceanography, under the direction of James Harris, Sr. to study integration of proximity warning indicators. The project is also concerned with a variety of aspects of visibility at various times of the day for various positions of maneuvering aircraft. A major problem that has emerged from evaluations of causal elements in aircraft accidents is maintaining wind screen transmittance. Visibility through the wind screen has been severely reduced in some instances by the collection of matter on the wind screen from bugs that are crushed against it during flight. Such a circumstance may well have contributed to at least one major mid-air collision.

Some work that is planned includes the analysis of dynamic visual scenes, i.e., scenes that are changing constantly because the aircraft is moving, particularly during landing; work with thresholds for the detection of moving objects, which is of interest to FAA; and additional studies of visibility.

d. Miles Murphy of the Man-Machine Integration Branch talked on an "Eye Point of Regard Device." This device is a product of Systems Technology, Inc. It includes both an eye-movement device and a head-movement device. In one study of ILS approaches, published in 1969, the flight director was the major point of focus. Changes were observed between fixed-base and moving-base simulations. With motion and the angular acceleration cues it provides, the attitude indicator requires less attention. Research plans for the future include comparison of performance in

flight and in simulators with respect to eye movements. In earlier studies, no correlations were made between eye movements and what instruments were actually showing at a given point in time. This can now be determined with the newer equipment. A full field of the view available to the eye, along with an indication of the point at which the eye is directed at any given time, can now be obtained so that correlation studies can be conducted.

e. John Dusterberry, Assistant Chief, Simulation Sciences Division, presented remarks on "State-of-the-Art in Visual Simulation Hardware." There is a wide variety of visual simulations that include optical systems and CRT displays. A variety of unique devices has been developed in each of these categories. One interesting optical technique is the shadowgraph. Northrop Aviation, for example, has developed a horizon projection system that presents a shadow horizon against a screen. The technique affords a valuable magnification of the image and thus permits the use of relatively small components for generation of shadow pictures. The so-called de Florey System employs a pointlight source and transparencies. North American Rockwell in Los Angeles now has one of the most advanced systems of this sort.

Another procedure involves the use of motion pictures. The VAMP (Variable Anamorphic Motion Picture Projector) System of Link Aviation employing 70 mm film with just half of the frame used is an example of this type of equipment. It is a very expensive process. VAMP has a resolution of approximately twice that of camera systems. There are a variety of inventions and ideas for the employment of motion pictures that have not yet been successfully implemented, but additional developments in this area may be anticipated. Projection systems for displaying motion pictures over a full 360° now exist and might be utilized for simulations. The problem of devising some method for the use of photographic film that would permit a simulation of the direct viewing of the surface of the earth and at the same time allow 360° maneuvers remains a difficult if not insoluble problem, nonetheless.

Another major type of system, which was distinguished by Dusterberry from the optical systems, although optical components are of course included, is that of CRT presentations. Such systems permit the utilization of electronic

and electromagnetic storage devices with selective access to a variety of visual protrayals. They also have some advantages for the transmission and reproduction of a visual scene. They remain the basic component for any device that will rely on computer-generated simulations of the visual world. Image generation with such systems may be based on the use of a camera and a scale model of the visual world, a flying spot scanner procedure, or a computer-generated image that is entirely simulated. Link Aviation is currently in preliminary stages of work on computer-generated displays.

A hybrid system is also under consideration, one in which computer-generated information and information derived from a scale model would be combined. Such a procedure may be employed with the F4E Trainer under development for the Air Force. The display will consist of a visual field of 160° horizontally and 90° vertically. Twelve CRT displays will portray computer-generated information upon which a VAMP-generated display will be superposed for high resolution information. The Ames Laboratory is now attempting to obtain a three-cell system in which a computer-generated display will be linked with a camera model system.

Other systems under consideration include those which will employ lasers and holographic displays, although the latter must be recognized as long-term development projects.

The various displays employed include the CRT monitor with collimation, a projected image on a flat screen, a display presented by means of a spherical mirror for the saving of space with a given large field of view, and a system that will include some of the advantages of a collimation system but for which there is no exit pupil. In a collimation system it is necessary for the observer's head movement to be narrowly restricted. Otherwise, gross distortions occur and portions of the image are no longer visible. A "no exit pupil" system permits a much greater range of head movements without distorting or cropping of the display. REDIFON is now working with a 48° x 36° ellipsoid mirror. It is hoped to compare such a system with a collimation monitor system and with a degraded collimation monitor system that matches the performance of a projection system.

A major problem with simulations rests with the fact that, as altitude is reduced, resolution tends to decrease

disproportionately relative to resolution that can be obtained from the cockpit of an aircraft. In order to offset this effect to some extent in the simulators at Ames, a scale of 600:1 has been employed rather than the original 1200:1. A Plumbicon tube has been employed rather than a Vidicon for the pick-up camera because it is more reliable and it reduces lag time by a factor of about 1/5. Link Aviation is currently working on a visual simulation and motion device for Northwestern Airlines. The visual portion of this device is essentially a copy of the REDIFON simulator. American Airlines has five REDIFON Systems installed at its training center in Fort Worth, Texas. These are built by REDIFON Air Trainers, Ltd., Aylesberry, England, for commercial aircraft and by REDIFON Air Trainers, Ltd., Crawley, Sussex, for European and British Air Force training devices. The belt model simulator, formerly built by GPS, has a characteristic of receding focus with increased speed in simulation. Scheimflug Optics result in the appearance of leaning buildings. A final comment was made on pick-up cameras to the effect that the SEC Vidicon is a bit more sensitive than the Plumbicon.

3. Miscellaneous

A highly schematic computer-generated display system was observed briefly, and new lens development for picture collimation was examined.

It is clear that extensive work has been conducted and is in process at the Ames Laboratory on the problems associated with visual simulation. A number of highly qualified persons in this laboratory are giving the problem serious consideration, and they are in close touch with others in other government laboratories and in industry. They appear to be well informed on problems and limitations associated with visual simulation.

A variety of information was provided in the form of graphs, tables and published papers. One of the most valuable is a summary of information concerning simulator facilities available at the Ames Laboratories prepared by George A. Rathert, Jr., Chief, Simulation Sciences Division.

C. GENERAL ELECTRIC COMPANY ELECTRONICS LABORATORY, SYRACUSE, N.Y.

1. As a result of preliminary arrangements made with Mr. C. H. Ide of the Binghamton plant of General Electric, a visit to the Electronics Laboratory at Syracuse was arranged for October 29, 1971 to discuss the state of the art of electronic generation of visual displays with Mr. Rodney Rougelot, Manager of the Visual Simulation Subsection at General Electric in Syracuse. It is in Syracuse that virtually all of the technical development work in this area is being conducted. Their present approach is to employ a color television picture tube and to present information on this tube via a common raster-type display which depicts the visual world. The display is entirely electronically generated, i.e., at no stage is any physical model of the real world or photograph of the real world employed. This procedure is very frequently referred to as the computer generation of visual displays, but this is misleading. It creates the impression that with appropriate software, any one with a sufficiently powerful computer may be able to generate" visual displays. This is not the case. The misunderstanding has led a number of individuals and agencies to request the "program" from NASA, Houston for the computer-generated display which is now in operation there. Actually, the electronic generation of visual displays requires certain highly specialized equipment. The circuitry and techniques are basically those of computers, but the system is a special purpose system.

2. The system permits the use of a limited number of "edges" for the creation of a picture. Edges are used for the depiction of ground terrain, objects on the ground, and objects which may move in relation to the ground. The computer stores sets of coordinates which define plane surfaces arrayed in three dimensions. Some of these surfaces may serve to define objects such as aircraft. Appropriate programming is included for the representation of dynamic characteristics of any given aircraft. Appropriate computations are made for aircraft motion in response to control surface deflections introduced by pilot performance at the aircraft controls as a function of the speed, the altitude and any other relevant variables for a specific situation. This system is then incorporated in a loop which includes appropriately loaded cockpit controls, an instrument display and the human operator. The manipulations of the cockpit controls result in appropriate changes of instrument indications and in the presentation on the television picture tube appropriate for any changes in perspective of the three dimensional visual world (as stored in the computer coordinate system) which should accompany the computed motions of the aircraft as a

result of the pilot's actions. For the pilot, the loop is closed both through instrument indication and the TV depiction of the real world. The results of his activities are presented to him visually in these two ways. Results of his activities may also be fed back to him via motions which are generated as a result of his control operations in those simulators which include motion capability.

3. The nature of the effort now being undertaken at the General Electric Company was described by Mr. Rougelot and several films were observed which provide an excellent illustration of the capabilities of the technique. These films were made by actually photographing a TV picture tube on which the visual information was displayed. With limited computer capability, it is possible to operate at a much slower rate than real time and to create motion pictures which depict the results one would achieve with greater computer capability, or a larger number of "edges" in the system. This technique is quite convenient for obtaining a very accurate illustration of what may be achieved by extensive elaboration of the electronic system before it is actually undertaken. There appear to be certain limitations and certain advantages of electronically-generated displays and it may be useful to enumerate some of these as they emerged from our discussions at the General Electric Company.

   a. Limitations

      (1) As a result of the limitation on the number of edges which can be employed, the procedure has been adopted of constructing objects out of a limited number of flat planes which in turn are defined by three or more edges. Smoothly curved surfaces such as the fuselage of an aircraft are thus replaced by a small number of plane surfaces. Shading is achieved with variation of the brightness of individual flat surfaces. Any given surface is homogeneous with respect to color and brightness for a given perspective. The shading of a given surface may be changed with changes in perspective. Even within these limits, a rather remarkable realism has been achieved with the limited number of edges now being used. The limitation is currently both storage capacity and computing power.

      (2) With the limited number of edges which can now be employed, there is a distinct limit on the amount of spatial resolution which can be achieved, quite

independent of the inherent limitations of any television raster type of presentation on a color picture tube. As the system is now programmed, small elements of detail on the ground plane have a scintillating character when they appear in the region of the distant horizon. It is in this region where they must be smallest on the display, and it is as if they are being shifted, somewhat randomly, from one to another of the limited number of computer coordinate system locations available when their size approaches that of the resolution limits of that coordinate system. Rougelot has indicated that this is in part the result of inappropriate programming and that it can be easily and inexpensively improved.

(3) Straight line elements presented on the raster type of display appear quite good when they are exactly horizontal, i.e., in line with the scan lines of the presentation. They also look reasonably good when their orientation does not deviate greatly from vertical. Unfortunately, when a straight horizontal line in the presentation begins to deviate from the horizontal, as would the horizon line, for example, when an aircraft in straight and level flight goes into a bank, difficulties arise. The straight line breaks up into a series of straight lines, each horizontal with respect to the television picture tube. They are segments of the raster lines of the display. The less the deviation from horizontal, the longer are these segments. As a result, edges in the presentation assume a somewhat serrated appearance as they move through various orientations on the display. This limitation is slightly disturbing to the viewer, but not extremely serious. It cannot easily be remedied without the use of greatly increased image-generating capacity, in all probability.

(4) A cartoon-like quality of these displays is heightened by the complete lack of any aerial perspective effect in most of them as they are presently employed. In the real world, atmospheric dispersion results in a muting of brightness and color differences with distance even in the absence of any fog or significant amounts of haze. Fog and haze can be introduced electronically at the present time. Presentations in which some "fog" has been introduced seem much more realistic than those without it. Fairly complete

data are available on the aerial perspective effect (Scripp's Institute of Oceanography Visibility Laboratory). The limited degrading of brightness and color differences with distance which occur in the real world could probably be achieved with the fog simulation circuitry fairly accurately. If this were done routinely, it probably would result in a much more realistic appearing presentation.

b. Advantages

(1) Electronically-generated displays include no mechanical components which may introduce lags or dead zones or mechanical inertia effects that will serve to limit the fidelity of the display with respect to relative visual motion effects. The lack of any such mechanical elements permits complete freedom for continuously maneuvering through 360^{o} rotations about any axis without the need for slip rings and without any hard wired connections which would impose limits.

(2) It is a simple matter to alter the perspective from which an electronically-generated display is observed. It may be from a maneuvering aircraft observing the ground, or from one maneuvering aircraft observing another. The same basic equipment is employed for any of these options.

(3) There is no serious limit on the range of flight that can be accomplished in any direction. Terrain simulation can be stored which will permit continuous straight-line cross-country flight in any direction. The same pattern might be used for any direction with or without rotations of its elements or several alternative patterns might be included.

(4) With all aspects of simulation electronically controlled, variations may be introduced easily and simply with respect to such dimensions as colors, color balance, luminances and their ranges, and the nature of runway lighting at night with respect to timing, color and spatial distribution. The detailed nature of the entire outside visual world in the vicinity of an airport or for any aspect of the ground plane can be altered by the simple expedient of a change in information stored in the system. Different airports may be maintained on punched paper tape, on cards or on magnetic tape for ready accessibility.

(5) With improvements in the state of the art, and a reduction in costs of computer storage capacity, both in terms of space and financial costs, it will probably be possible to update equipment installations without complete replacement.

(6) Implicit or explicit in all of the above listed advantages is the great flexibility which would seem to be afforded by electronically-generated displays. It does not seem likely that they will go through a limited period of usefulness followed by obsolescence, but rather that they may evolve as the state of the art evolves. Of course, any radical change in techniques employed might render an electronically-generated visual simulation obsolete, but this possibility seems relatively unlikely for the immediate future.

4. The films developed by the General Electric Company which provide an indication of what may be achieved with a larger number of edges than those now employed in real time have been displayed widely. Some viewers of these films have assumed that they represent conditions which are not now technically feasible in real time. This is incorrect. Displays as presented on the films are now realizable. The limitation is one of cost for equipment and storage capacity. Economically, such systems may not now be feasible under the present conditions of relative austerity, but technically they certainly can be realized. With improvements in storage techniques and computer circuitry, it is probable that costs will be significantly reduced and electronically-generated displays of significantly greater realism will then become economically achievable.

   Rougelot indicated that the most sophisticated electronically-generated display now in use is located at the Manned Space Flight Center of NASA in Houston. Tentative arrangements were made to visit that facility sometime in December.

D. AMERICAN AIRLINES FLIGHT ACADEMY, FORT WORTH, TEXAS

1. A visit to the Flight Academy was arranged by Dr. Robert Houston, who is Director of Flight Training for American Airlines. Dr. Benson and I met with him in his office and provided him with a brief indication of the task of our working group. We indicated that our purpose was to survey current activities in simulation of visual world for use in flight simulation and to attempt to identify those problem areas of national importance. American Airlines currently

has what is probably the most advanced flight simulation for pilot training of any of the commercial airlines.

2. Dr. Houston provided us with a variety of information on the general subject of simulators as these are used in training. Training facilities vary considerably among the different airlines. Currently, the FAA has inadequate facilities for the training of its own inspectors. This is a matter of personal concern to Robert Stevenson, Director of Training for FAA in Washington. No facilities for 747 training are available at all within the FAA organization. Inspectors who certify pilots must be trained and some are being trained by various airlines. During the discussion, it was pointed out that U. J. Kampsen of Trans-world Airlines had indicated in a memorandum to the FAA in February of 1971 that there are 16 maneuvers which must be done in flight and cannot be accomplished in simulators. Houston indicated that the number of maneuvers varies with the specific airline company and with the aircraft as well. American Airlines has been making a serious effort to reduce the number of maneuvers for which training in an aircraft is required prior to certification. They are currently conducting an experiment with the cooperation of FAA. Captain Sam Page described it to us in some detail later in our visit. It consists of an engine loss maneuver with the resulting asymmetrical thrust. Pilots are trained in recovery on the simulator and do not encounter the problem again until their checkout stage in the aircraft. FAA inspectors are now grading them on their performance in this maneuver during the checkout stage and to date they have been performing quite satisfactorily. If the remaining pilots in the experiment are able to execute the maneuver satisfactorily the first time it's encountered in flight, it is probable that the FAA will permit learning of this maneuver in the simulator. For the American Airlines program, there are currently 4 to 9 maneuvers which must be learned in flight by their pilots. These include situations in which no flaps are available, in which there is an engine failure in landing, in which a circling approach is required and with a coupled ILS landing. American Airlines is having considerable success with their simulation training program and finds a very high degree of pilot acceptance. Amount of time required for training in flight has been grossly reduced since the beginning of the program in Fort Worth in 1966.

One problem of minor concern is the difference in transfer from simulator to aircraft as contrasted with aircraft to simulator. In addition to initial training in a given aircraft type, pilots must undergo recurrent training periodically.

After having flown regular flights on the line in an aircraft type for some time, they return to the flight academy for additional simulator work. There appears to be little positive training and perhaps some negative training in transitioning from the aircraft to its simulation at the flight academy. This is described as 95% transfer to the aircraft and only 5% transfer to the simulator, but these percentages are not based on any quantitative assessments. The reasons for this situation are not entirely clear. It has been variously attributed to inaccuracies of the motion simulation (particularly with respect to washout), incorrect visual cues in the simulator, and possible interactions among various dimensions of the simulation. The training personnel at the flight academy worked for some time with the DC-10 simulation in which motions of relatively large amplitude were being employed. So much of the motion ranges were utilized that there was insufficient distance remaining, after a yawing maneuver for example, for the washout to be accomplished smoothly. This problem was completely unnoticed by the training personnel who were working with the simulator almost daily, even though they were also qualified pilots and were flying the aircraft periodically. Pilots without simulator experience pointed out the difficulty and it was then immediately recognized by the regular staff and corrected. The problem of what may be called asymmetrical or nonreciprocal transfer from simulator to aircraft and back is discussed further below.

The ultimate criterion of the value of a simulation is whether a man trained in the simulation can fly the aircraft satisfactorily. If unable to do so immediately upon transition, how much additional training time in the aircraft is required? "Satisfactorily" here refers to acceptable performance of all of those maneuvers required by the FAA for certification in the aircraft by an FAA inspector. American Airlines has now obtained substantial justification of the use of simulators based on records of the last five years at Fort Worth. Flight time required for qualification in a new aircraft by experienced pilots has been reduced by a factor of from 5 to 10 times. The order of time required for training in flight prior to 1966 was approximately 20 hours. Since then, it has been possible to reduce flight time drastically. In the DC-10 program, the average flight time has been 2 hours and eleven minutes for both training and checkout with the FAA inspector. One pilot required only one hour and nineteen minutes in the aircraft. Although 18 or twenty hours are required in the simulator, this much actual time in the simulator can be obtained with less total

time obligation than the same number of useful hours in flight would require. When the cost of flight (probably $700-$1,000 per hour in most large commercial aircraft) and the matter of safety are considered, the advantages of simulators are clearly evident. The subject is reviewed in a paper presented by W. P. Moran at the Fourth International Simulation Training Conference, May 13, 1971.

3. Houston presented a brief summary of the entire training program at Fort Worth with slides and a motion picture illustrating the development of the program and its underlying philosophy. Basically, concern is with training to proficiency as assessed by behavioral criteria. Since the original creation of the flight academy, there has been a transition from lecture type of training to more and more individual, hands-on training in all aspects of the program. Slides and audio tape recorded training sequences have been developed for all aspects of the aircraft system training. Individual crew members may work at their own pace. When the required level of proficiency has been developed in a given stage of the program, the trainee may move to the next stage. In general, a given group of trainees moves through the program at about the same pace in terms of total number of days required, but some do require fewer hours than others. It has not yet been possible to make the program a truly individual one with respect to the time requirement. The result of the effort has been a greatly increased motivation on the part of trainees, with substantially more efficient learning, in the opinion of those responsible for the program. Although serial programs are now being employed, computer-assisted instruction with branching programs is under consideration. Additional information on the training program is available in another report which was presented by Moran at the Fourth International Simulation and Training Conference.

   Simulation work for flight crews is done in the same building as is ground training. Facilities now available include simulations for the 707, 727, 747, and DC-10, as well as a simulation of the Cessna Citation which has been developed from what was originally a BAC-111. The latter simulation is probably the only corporate jet training device which includes motion simulation about three axes and a simulation of the external visual world. Five visual simulations include REDIFON vertically mounted scale models and the moving belt (originally GPI) type. These may be programmed into 11 different cockpit simulations each of which employs three projectors mounted on the top of the cockpit and a screen. As presently used, these projectors provide an appropriate view of the screen for only one occupant of the simulation.

The view can be slewed from left to right to accommodate either the occupant of the Captain's seat or the First Officer's seat. Cockpit windows are painted out except for a central region similar to that which would be left clear by windshield wipers in order to obscure edges of the screen. The vertical extent of the view is approximately 40° with an approximately 50° horizontal view with the present configuration.

These simulators are currently scheduled for use on a sixteen-hour day, seven-day week basis. They have actually been available 99.5% of the time. The visual simulations have been available 99.2% of the time. The visuals, including 11 projectors, the models, TV probes and associated computer equipment are maintained by a staff of sixteen working on three shifts. The personnel allowance for this work is 22, two for each projector, but, apparently, 16 is a sufficient number. The total staff of the electronics group is now 80. The 747 simulators were made by Link Aviation; the DC-10s by REDIFON. The mechanical mountings for motion are quite different for these two types, but both appear to produce an acceptable result.

There has been some discussion of the seriousness of the limitation on the size of the visual field. During his presentation to us, Houston showed us a movie in which Moran flies a simulator through a circling maneuver with the limited field of view. He is arguing for the adequacy of the limited lateral view in flying such maneuvers and bases his case primarily on the ability of a pilot to perform satisfactorily with reasonably good outside vision, even though limited laterally, if he is familiar with the terrain.

4. Various simulators were observed in operation and some time was spent observing and "flying" the DC-10. The remarkably successful DC-10 program was discussed with Captain Sam Page who has had a major responsibility for its implementation. He believes that in training with simulators the student should never be permitted to encounter a situation which he cannot readily handle. That is, the difficulty of the task with which he is confronted must be increased gradually as his competence increases over the training period. Such a procedure would certainly be employed in the aircraft for reasons of safety. Page believes that it is extremely important to follow this procedure in simulators as well, in order that the self-confidence of the pilot trainees be maintained and also in order to maintain their confidence in and acceptance of

the simulator as a training device. He has noted a tendency on the part of pilots working in the simulator to overcontrol. This is gradually overcome with practice. This is sometimes observed in aircraft also and reasons for it are not clear. In the simulator, it may be the result of some aspects of the motion of the simulation. During the training program, situations which are very unlikely to be encountered in the aircraft will not be employed in the simulator, even though they could be used with complete safety. Page demonstrated several extremely difficult landing situations with breakouts through clouds of very low ceiling. He also demonstrated a stall maneuver in order to permit us to experience the limits of the motion capabilities of the simulator installation.

5. During the course of our visit, an interesting and continuing discussion developed concerning reasons for the nonreciprocal transfer from simulator to aircraft and from aircraft back to simulator. The major participants in this discussion were Houston, Page and R. O. Besco, an American Airlines First Officer, who also has a Ph.D. in Psychology from Purdue, specializing in Aviation and Engineering Psychology. Page tentatively attributes the situation to the fact that all cues available in the aircraft are not available in the simulator and that some of those available may be slightly inaccurate. When pilots transfer to the aircraft they are able to use all of the cues they have learned in the simulator plus additional ones. With extensive aircraft experience, the nature of the cue set upon which performance is based may change, such that some cues unavailable in the simulator come to be used. In addition, subtle interactions among cues in various dimensions are learned at a highly refined level in the aircraft. In recurrent training in the simulator after flight experience, pilots are faced with an impoverished set of cues, and, as a result of extensive experience in the aircraft they tend to respond to anomalous or slightly inaccurate relations among motion and visual cue systems in a maladaptive fashion. As a result, some negative transfer occurs from aircraft to simulator. Although the issue was not discussed, this raises some question as to the values of recurrent training, the frequency with which it should be employed and its impact on the future acceptance of simulators by pilots when transitioning to other aircraft.

Besco is of the opinion that the principal source of degradation of fidelity in the simulator is in the visual simulation. He believes that the equations for computation of changing visual perspective may not be precisely right and that this

leads to some difficulty when pilots depend upon outside visual reference. The most serious difficulty would appear to arise in connection with lateral control, particularly during landing. Houston appeared to be somewhat closer to the position of Page on the issue. During the discussion, several interesting points were brought out. All of the experienced participants in the discussion agreed that pilots fly simulators better on instruments without external visual reference simulation. Page stated that, without question, pilots perform better on the simulators at the flight academy when motion is included than when the motion cues are eliminated. These facts appear to support Besco's position. Commenting on the issue during a later discussion, Mr. F. Wirth, Director of the Electronics Division, indicated that he believes the major source of the difference is psychological. Pilots are very much aware of the difference in the situation between an aircraft and a simulator and they know that they are not subject to the same penalties for overcontrol or error in the simulator. By chance, an American Airlines crew member accompanied us in the cab when we left the flight academy. In response to an open question as to how pilots evaluated the simulation training, he replied that the visuals had not been very good until recently and that they are still not perfect but are now acceptable. He stated that the pilots' main concern during their training and recurrent training in Fort Worth is to get through as quickly as possible. There is a widespread belief among them that this can best be accomplished by "flying the gauges" down to an altitude of 50 ft., because the visual motion which should accompany aileron control is "too sluggish." It would appear that pilots, among whom word probably gets around fairly rapidly and of whom Besco is a not quite representative example, have decided that it is the visual simulation part of the total simulation situation that is inaccurate.

6. Wirth of the Electronics Division was questioned at some length regarding the response characteristics of servos which control the TV probes employed for scanning of the models. He replied only that he thought they were excellent and gave rise to no significant inaccuracies. He emphasized that they required very little maintenance. He was unable to provide any information concerning techniques for their calibration or for checking the accuracy with which visually displayed information matched that called for by computer programs.

7. The American Airlines simulation facility is primarily for training and in this application it has proven remarkably successful. The saving in time required in flight for

training has exceeded that predicted for 1975 already. Those responsible for the management of the program are quite sophisticated with respect to training techniques and are obviously willing to experiment for the improvement of training procedures. There is little or no possibility for systematic experimentation with respect to technical aspects of the simulation, however. As indicated above, the extent of motion and the nature of washout has been adjusted on the basis of subjective impressions of experienced pilots, but the training load at the facility is too great for detailed experimental evaluations of these variables. The visual information concerning the outside world is presented with a system based on theoretically derived equations for the transfer function relating pilot control manipulation and TV probe motions. It is unlikely that any test of the actual response characteristics of this system as compared with those desired or with some optimum standard has been made.

8. It is evident from our visit to American Airlines that there are both advantages and disadvantages associated with a commercial simulation installation. The fact that there is a quantitative criterion for assessment of the success or failure of the operation is in most respects an advantage. The operation must be economically justified. In short, it must permit the saving of money, increased safety and increased availability of line aircraft for revenue flights. On the other hand, the realization of these goals and the very heavy operating schedule preclude the availability of the facility for systematic research activities directed toward further improvement. The current record of the installation, particularly with respect to the DC-10, suggests that there may be relatively very little room for further improvement as measured by the criteria of primary concern to the company.

E. MANNED SPACE FLIGHT CENTER OF NASA, HOUSTON, TEXAS

1. The visit to the Manned Space Flight Center Simulation Branch was arranged to coincide with the visit by General Electric representatives from Syracuse, including Rodney Rougelot, who is manager of the visual simulation subsection. Our concern was with an electronically-generated visual display which has recently been improved substantially by General Electric Company. It is currently used for simulations in connection with the space shuttle vehicle landing problem and for the docking maneuver required in linking with an orbital space station. The space shuttle vehicle (SSV) simulation provides a view of terrain and an airstrip located between two rows

of mountains. The terrain is marked with outlines of fields in various colors, which presumably correspond to different crops or to bare earth without vegetative cover. During their visit, the GE respresentatives made a punched tape for changing the colors of various sections of the terrain in order to make them appear more realistic. The punched paper tape permitted a change in the computer-stored information. With different tapes, changes in the color relations of the terrain could be accomplished very quickly.

The SSV simulation includes a partial view of the nose of the craft. A cabin mock-up is available in which the visual simulation is presented on a television picture tube which is viewed through a collimating lens. Equipment for the visual presentation is mounted on a modified forklift truck for facilitation of interchanging from one installation to another.

2. Problems of line break-up and scintillation in the region of the horizon and for small elements in the picture were observed as they had been at the General Electric plant in Syracuse. The picture, generated in real-time with the possibility of closed-loop control, was impressively good, although it did not represent nearly as many edges as the best presentation which has been developed with film techniques. The latter serves only to provide a sample of what may be achieved technically as noted in an earlier report. At present, this system is the best available for real-time, closed-loop operation. It consists of 320 edges, a substantial improvement over the 240 available prior to the recent modification. The actual improvement of the system is greater than that implied by these numbers. In the old system, each time a continuous straight line in the display was interrupted by an intersecting line, an additional edge was required. In the new system, only one edge is needed for any straight line independent of the number of times it is intersected. A 20 Hz. scanning rate has been employed with a 600 line raster in order to gain some spatial resolution advantage with a sacrifice in temporal resolution. Picture tubes viewed directly are seen to flicker quite obviously, but with the attenuation which results from viewing through the collimating lens, there is no evidence of flicker. The picture is somewhat stark as a result of the large patches of homogeneous color. It could be improved by the introduction of electronically simulated fog.

3. Monitoring scopes present the picture with a stable horizon. The nose of the vehicle moves corresponding to banking maneuvers. Within the simulation cockpit, the horizon moves as it must for any inside-out simulation. There is no motion

in the simulator as it is presently configured and the movement of the external visual world seemed quite realistic but somewhat disturbing as viewed through the collimating lens. Some visitors have been unable to remain in the simulation because of nausea induced by the simulation of motion of the external visual world without concomitant motion cues within the simulated cockpit.

4. The general opinion prevalent among those at NASA who are responsible for simulation is that electronically-generated displays represent the proper approach to simulations of the outside visual world for any future research. The primary basis for their opinion would appear to be the quite considerable flexibility afforded by such installations. This view is in contrast to that expressed by several of those who were contacted at American Airlines. The latter felt that the use of models represented the best solution at the present time. It is fairly clear that the difference in opinion can be attributed to differences in the functions of the two installations. The NASA group is concerned primarily with research and development, while those at American Airlines are concerned with training for existing commercial aircraft. At present, there are no data based on carefully controlled experiments which support the arguments that either models or electronically-generated displays are superior for any purpose, training or research and development work. One experiment which has been reported by the NASA investigators indicates that, based on such quantitative cues as touch down point and sink rate in landing, there is no difference between computer-generated displays and displays derived from scale models with color vision scanning when all other factors are optimized.

5. The Air Force will soon contract for a large training simulator which will permit a relatively wide field of view. It is probable that this simulation will be achieved with electronically-generated displays. Although it is not yet certain, there is a good possibility that the contract will be awarded to the General Electric Company. A wide field of view will be achieved by the use of a number of television picture tubes arrayed horizontally. The spacings between adjacent tubes will be made to appear as parts of the window frame in the cockpit simulation. This installation, if and when it is developed, may be available for additional experimental work.

F. PROPOSED TOPICS FOR DISCUSSIONS OF THE WORKING GROUP AT THE JANUARY 13TH MEETING, ORLANDO, FLORIDA

Memo to members, Vision Working Group 34, Visual Elements of Simulation, December 30, 1971, from J. L. Brown, Chairman

It is the purpose of our working group to review problems associated with inclusion of external visual simulation in flight simulators. This is a problem of great concern to representatives of the FAA, of NASA, and of the commercial airlines. There are a number of individuals deeply concerned with the problem more knowledgeable than many of us on this working group, who are devoting a large measure of their activities to the problem's solution. We are therefore not presuming to solve the problem. Rather, our purpose is to provide a broad, and perhaps in some ways, new, perspective from which to view the problem with the hope that we may be able to identify explicitly areas in which research may be important. In preparation for our meeting in January, I have formulated a number of questions. The significance of these questions probably varies from the trivial level to a level of considerable importance. I hope that with these as a starting point, we will be able to generate useful discussion and that the proceedings of our meeting may serve as a point of departure for continuing useful research on the problem.

As background for our discussion, it will be useful to review several references. These include a general summary of the problem of simulation fidelity and transfer of training by Gerathewohl, a summary report on techniques for visual simulation by Mark Lewis, a memorandum prepared by Patton and Sadoff of the Ames Laboratory of NASA with associated references, my preliminary report on activities at Langley and Ames, and a second report concerning visits by Benson and myself to the American Airlines installation at Fort Worth and the Manned Space Flight Center of NASA in Houston. As you will see, the questions which follow are in some instances drawn directly from some of these references. It would be useful to attempt to order them according to their importance in your opinion and to make some judgment as to whether important areas for research have been omitted.

The problem for which simulators may provide an answer is that of learning to fly complex and expensive modern aircraft economically and safely. Any learning which can be accomplished in a simulator which will transfer directly to performance in the aircraft can be done at less expense and without risk of major equipment loss or injury. Since some aspects of aircraft control depend upon an exterior view from the aircraft of the outside visual world, the visual world must be simulated to the

extent that cues derived from it need be employed by the pilot. Maneuvers of particular concern involve landing, takeoff, and circling maneuvers associated with these tasks. In addition to the problem of learning to fly an aircraft, a number of additional problems may be undertaken with simulators. These involve research on the limits of pilot capability, control system design, new aircraft design and any problems which arise in connection with the invention, design and development of new devices for which man may serve as a controller.

1. What elements of the visual world must be simulated and how completely?

    a. Range of daylight luminances

    b. The field of view through the wind-screen

    c. The range and accuracy of color rendition

    d. Conditions of external illumination, both real and artificial as encountered at night

    e. Spatial detail

       The extent to which simulation equipment will permit the imaging of visual detail on the retina as contrasted with the sharpness of detail encountered in actual view through an aircraft wind-screen. For electronically-generated displays which do not involve the use of a model or actual photographs of the real world, spatial detail may be degraded by the limitations of the computer systems employed. The significance of this must be assessed.

    f. Visibility through fog and rain

    g. Motion characteristics as portrayed by relative motions in the visual display

    As pointed out in some of the reference material, particularly the report by Lewis, there are certain limitations inherent in various types of visual displays. Some improvements have been made since his report was prepared but the qualitative limitations he describes still exist. TV probes which scan models must be driven mechanically and equations which describe their desired motions for certain control manipulations of the pilot in the simulator must be worked out. They have, of course, been worked out, but questions are sometimes raised as to their validity. For example, it is difficult to determine the extent to which precise checks of the actual motion generated at the probe as compared to that commanded have been made. The probes are small and it probably would be impractical to mount accelerometers on them. The seen

visual motion as displayed to a pilot in a simulator is the important element here. Does it correspond with seen visual motion in the real world for similar conditions? Is there any way in which a quantitative assessment of the visual display can be made or must we rely on pilot opinion as to whether or not relative visual motions are acceptable? Pilots working with some of the best equipment currently available do not believe that the visual motions are portrayed exactly as they should be. Visual detail rendered on a TV picture tube is limited by the raster type display. The seriousness of this limitation becomes greater the closer the objects viewed. In computer or electronically-generated displays, unrealistic scintillations occur where attempts are made to render small elements of visual detail. Straight lines break up in present day simulations of this sort as they are tilted slightly from the horizontal. This is a consequence of the type of programs currently employed coupled with the horizontal scanning line technique now used. The seriousness of these factors must be considered.

2. How important is the range of terrain to be covered?

   With models scanned by a television probe there is a finite limitation which in present practice restricts the model to the immediate environs of an airport. In fact, the models are usually so small that it is difficult to execute a 360^{o} turn without going "out of bounds." Long cross-country flights are impossible with such a model. Where film strip is used, cross-country flights of some duration (22 minutes or thereabouts, according to Lewis) are a possibility but the pilot must fly in a grossly restricted corridor and little freedom of control is possible. On the other hand, the major areas of concern at the present time are for landing and takeoff. It is possible that the kinds of learning necessary can be achieved even with gross restrictions in the geographic range of flight in which direct visual contact is possible. On the other hand, if training involving external vision of the real world is necessary for any aspects of cross-country flight or terrain clearance, serious problems exist with the use of models as well as with photographic film. Are these problems insurmountable? If so, and a need exists for visual simulation under these conditions, is the use of electronically-generated displays the probable best solution?

3. What are the appropriate criteria for evaluation of simulators?

   a. If the basic problem consists of providing an opportunity for a pilot to learn to fly an aircraft with which he is

not yet familiar, the ultimate criterion rests with an evaluation of whether he can step into the cockpit of that aircraft and fly satisfactorily after having been trained in a simulator. The evaluation of this may be accomplished using techniques now employed by the FAA for certification of pilots. No quantitative measures are made for this purpose and probably none need be made.

b. Researchers are indoctrinated in the value and importance of reducing a problem to one of quantitative measurement. Is this in any way essential in connection with any aspect of the simulator problem? As indicated in some of the references cited above, measurements have been made of such variables as sink rate, vertical acceleration, touch down point and the nature of the pilot transfer function in control. Preliminary research indicates that some of these variables differ consistently in simulators as contrasted with actual flight. Specifically, sink rate is almost invariably higher in a simulator than in actual flight. Is this difference important? If, in spite of the difference, a pilot who has had no experience in a given aircraft can transition from the simulator to the aircraft and fly satisfactorily in accordance with the criteria of FAA inspectors (whatever these may be) then differences in quantitative measures of this sort need be of no concern. On the other hand, ideally, investigators would like to see a simulator facility in which any quantitative measures of pilot performance would, after sufficient training, accord with those obtained for an experienced pilot in actual flight. The assumption is here that the pilot would then have demonstrated his ability to fly the aircraft. Even this should be demonstrated empirically, however. It is logically possible that a pilot who produced the proper quantitative values of performance for a detailed list of indices when working with a simulator might nonetheless be unable to perform satisfactorily without additional training in the aircraft. It has already been demonstrated at American Airlines' facility in Fort Worth that pilots trained in the simulator whose quantitative performance may differ slightly from that desired in the aircraft do fly the aircraft satisfactorily, nonetheless. The implications of this discussion are that certain cues in simulators differ from those available in aircraft or, alternatively, certain cues available in aircraft are absent in simulators. We know that, at least with respect to motion, all of the cues can probably never be included in a simulator. To what extent is this a serious limitation?

4. To what extent are interactions among various sensory dimensions of the simulation of importance?

   The pilot of the simulator receives cues from his instrument display, from the controls which he is manipulating in terms of their resistance to motion, from the simulation of the visual world, and from the simulation of motions of the vehicle. Probably the most difficult of these to simulate with complete fidelity is that of motion. Nonetheless, by taking into account threshold sensitivity of the vestibular system to angular accelerations and employing "wash out" techniques, subjectively satisfying motion simulations have been achieved. Slight incompatibilities between visually presented information, both from instrument panels and from simulated exterior views, and motion do occur in most simulators, however. To what extent is this important? To what extent does it reduce the value of the simulator as a training device? As a research tool? The fact that pilots perform in a simulator more nearly as they do in an aircraft when the visual display of the external world is eliminated has led some to conclude that the external visual simulation is inaccurate. It has also been noted that pilots perform less well flying just on instruments than they do on instruments along with motion simulation. (This, of course, varies with different simulators but refers to the type of simulators now employed by major airlines.) This latter fact has been interpreted to indicate that the motion simulation is valid. It has been the basis for arguments that it is not interaction between motion and vision that causes differences in simulator performance, but rather, inaccuracy of the visual simulation. Is this conclusion justified?

5. Of what value is the achievement of high "face validity?"

   The acceptance of simulators as training devices depends to a large measure on the face validity of the simulator as assessed by the trainee. At least, this is the opinion of those who work with such devices. It is possible that certain aspects of simulation which provide face validity may be unessential for effective transfer of training with completely unbiased trainees. Elimination of certain aspects of simulation which add to face validity but not to the actual validity of the device might permit considerable savings. Conceivably, although it is perhaps unlikely, the actual validity might be enhanced by elimination of some of the "window dressing." To what extent is it worthwhile to pursue this issue further? Although the researcher would like to discount the fact on some occasions, it remains important to have the acceptance and support of the ultimate

user of the device and if certain "gimmicks" are necessary to achieve face validity in order to gain such acceptance and support, then they probably must be included. Should this issue be investigated to any extent? To what extent will working pilots accept a simulation device which appears to be degraded but which nonetheless includes all of the cues that are truly important?

6. What are the most important lines of investigation which should be pursued in the future?

   Much of the discussion which is included above relates to aspects of an external visual world simulation relatively independently of how the simulation is achieved. Some limitations of the use of models are implicit in the above discussion. Models are believed to be the best means of simulating by many of those faced with the practical problem of using simulators in the here and now. Electronically-generated displays have been criticized on the basis of the probability that they will never achieve the realism now possible with scale models. In view of the actual purposes for which simulators are to be employed, what is the merit of further efforts for development of electronically-generated displays? Where may energy best be expended, on displays that employ a raster type presentation, or on those which employ line element drawing type presentations on a cathode ray oscilloscope? At least one experiment which has investigated the matter gives some evidence that when other aspects of the simulation are optimum, color may be of little consequence. How can such dimensions of the visual world as color be evaluated realistically, i.e., in terms of the actual benefits which they afford as opposed to pilot opinion? The same question might be asked for virtually every other dimension of a visual display. Some argue that relative visual motion portrayal is the only significant issue and that such refinements as color, realistic range or luminances, and spatial detail are relatively unimportant. Can this position be tested quickly and definitively by experiment? Perhaps as a rationalization for the fact that the field of view of the simulated external visual world is curtailed with present day devices, some have argued that pilots must fly when much of the wind-screen is occluded by sticky snow so that the field of view is no greater than that afforded by present simulations. They argue further that, if pilots can learn to perform all maneuvers under these "worst conditions" then there is no need for providing them with optimum view. Is this a valid position?

7. Who should perform research and where should it be done?

   The kind of research which must be done on simulators is beyond the scope of capability of most universities. It may be done in government laboratories or in industrial commercial laboratories. A superficial view of the current status of the simulation problem suggests that a much greater degree of coordination than now exists would be desirable, however. Where it fits in with their regular training operations, it may be possible for the flight simulator facilities of airlines to be employed for some research. The utilization of this equipment for training is so high, however, that availability of special blocks of time for research purposes is unlikely. Can this working group lay out any reasonable program of proposed research which includes suggestions as to where it might be performed and who might undertake it? Or does such an effort, over and beyond the preparation of a specific list of research needs, penetrate the area of presumptuousness which we wish to avoid?

G. VISUAL ELEMENTS IN FLIGHT SIMULATION

Report of the Meeting of the Committee on Vision, Working Group 34, January 13, 1972

Arrangements for the meeting were made by Dr. James Regan of the Naval Training Device Center. After a brief meeting with Captain Frank H. Featherston, the Commanding Officer of the Center, and Dr. Hanns H. Wolff, the Technical Director of the Center, members of the Working Group adjourned to a meeting room for discussion of the problem of simulation of the visual world in a flight simulator.

Those in attendance at the meeting and their professional affiliations are given in the attached appendix.

The meeting was relatively informal and the specific items discussed covered a number of aspects of the general problem. The subject matter of discussion falls roughly into four general categories. Rather than to attempt a summary of the various points of discussion in the order in which they were presented, it seems more profitable to review material covered in each of the four general categories in turn. All of those present contributed to the discussion significantly. In many instances, their contributions are acknowledged in the following material. No transcript of the proceedings was made and it is not possible, therefore, to provide specific attribution for all of the comments and suggestions which were made.

1. A discussion of the various purposes of simulators

It was clear from the discussion that the major concern with simulators relates to their use for purposes of training and that in this area the major application is probably for training of commercial aviators. The use of simulators by the Air Force for training is also of considerable impoitance, however. In the military application, there is much greater variety in actual simulator requirements. Milicary utilization of simulators may be increasing and the proposed Air Force installation at Willicms Air Force Base using a computer-generated type of visual display may represent one of the most advanced simulators in the country when it is completed.

The airlines would like to reduce the actual amount of time spent in training in aircraft to an absolute minimum. In addition to the reduction in training hours in which serious accidents may occur, simulators are cheaper to operate than aircraft and aircraft freed from such requirements may be used for revenue flights. The present record of American Airlines in training its pilots to fly the DC-10 may be difficult to surpass, however. DC-10 pilots now require an average of only two hours, eleven minutes in the aircraft prior to flying line flights and one pilot has qualified with only one hour, nineteen minutes. There has been some discussion of possible repercussions of reducing training in the aircraft any further if, indeed, there may not be problems at the present level. Should a pilot who has had only one or two hours in an aircraft before a line flight be involved in an accident, the public reaction might be extremely severe. For this reason, it is questionable whether airlines will expend very much effort or money to improve simulators beyond their current level of development for commercial pilot training.

Kussell pointed out that an aspect of handling of large aircraft which may sometimes be overlooked is the problem of maneuvering after touch down, particularly on icy runways. Presumably, simulators might be developed for training in this area.

Military problems, including air-to-air interception and low-level attack flights, may require specialized devices for each new airframe and weapons system that is developed. The use of simulators for extensive training of Air Force pilots in relatively unique applications may therefore be less practical than is the use of simulators in commercial aviation.

The Working Group did not concern itself to any extent with applications of simulators for the experimental determination of a pilot's capability in novel situations, or the experimental evaluation of proposed new aircraft with characteristics differing from those with which pilots may be familiar. These are interesting applications for which simulators have been used in the past and for which they may be of importance to a limited extent in the future, nonetheless.

2. Techniques for the design and evaluation of simulators

Simulator manufacturers are provided with the best available information as to the aerodynamic characteristics of the aircraft to be simulated. The transfer function for an aircraft, or its equations of flight, are utilized in the design of the response characteristics of the simulator, both with respect to instrument displays and simulator motion characteristics where these are included. When a simulation of the visual world is to be included, relative visual motion must also occur in accordance with the way in which the aircraft would respond to specific control inputs. Only the instrument display may, theoretically, provide a completely accurate simulation of the response which would occur in actual flight. Motion simulations are approximations at best and their evaluation is highly subjective. The simulation of the external visual world can presumably be made quite realistic, but there are problems associated with the accomplishment of this. When a television camera is moved about over a three-dimensional model of the terrain, its motions must replicate those through which the aircraft would go for given control inputs by the pilot. Thus, the equations of flight which are used to compute the changing pattern of instrument information are also used to drive the 6^{o} of freedom mount of the television probe. This system, of finite mass, controlled by servos, may be expected to result in the introduction of some latencies and alterations of the desired result. Unless characteristics of servos and inertial characteristics of the physical elements are taken into account, the simulation will not be completely accurate. If servo lags, nonlinearities and other characteristics are known, it is probable that they can be compensated for. It is extremely unlikely that they cannot be absorbed within lags in the response of the aircraft which is simulated, for example. Nonetheless, it is unlikely that sufficient attention is being given to the evaluation of this dimension. In any case, information provided by instrument displays, the visual world and motion cues must all be compatible. It is to be expected that any lack of correlation would be found disturbing, particularly by an experienced pilot.

For computer-generated displays, there is no problem with latencies, nonlinearities or inertial characteristics of the display. There are questions, however, as to the accuracy of the equations which are employed for the generation of computer displays. Some approximations are used in these and it is highly probable that certain assumptions are made as to the significance of higher order terms which results in their being dropped. Visual displays may not be precise replications of those which would be encountered in the actual aircraft.

Collins suggested that a motion picture record of an instrument display, of the simulation of the external visual world and of the aircraft controls would permit measurement of the response of the system with respect to instrument display and visual world to a variety of step inputs into the control system. This would permit the measurement of the response characteristics of the system and an assessment of how accurately the desired conditions, prescribed by equations of flight, have been met. This is, of course, an open-loop evaluation of the system as Vogeley pointed out, but its purpose would be to measure open-loop response characteristics and a measurement of this sort would be of considerable value, at least for preliminary verification of the implementation of the aircraft transfer function. The reduction of data for continuous motion pictures of relatively complex maneuvers might prove difficult. It would certainly, as Vogeley again pointed out, require some form of computer processing. Russell indicated that National Airlines have already done some work with a photographic evaluation of simulator fidelity.

When the manufacturer of a simulator has done the best possible job of incorporating available information on flight characteristics into the simulator and its various dimensions, he will presumably check it out prior to delivery by having his own pilots "fly" the device. Glaring errors would certainly appear at this time and could, presumably, be corrected. When the simulator is delivered to the consumer, the evaluation process and "tuning" is continued. The criteria for this are largely subjective, but this must not be interpreted to mean that the procedure is a casual and unsystematic one. Usually, a rather large number of pilots will be asked to fly through certain maneuvers with the simulator. Their performance will be noted by a trained observer and their opinions as to the realism of the device will be solicited. Modifications will be made when these seem appropriate in order to effect improvements. An example is the alteration of the wash-out characteristics of the DC-10

simulator at American Airlines as noted in an earlier memorandum. Smith suggested that an even more systematic job could probably be done. He cited work which has been done on simulated automobile systems by McKnight. A set of 45 standard tasks was employed and systematic interviews were given to drivers after their performance of the tasks. This is apparently what is being done currently with simulators but perhaps at a somewhat less formal level. Odle indicated that this is a procedure being used by the Air Force. Regan suggested that there might be some value in involving experts in the design of instruments for the measurement of opinion at this stage in simulator evaluation. Certain quantitative indices of performance have been employed such as touch down point in landing, sink rate and other variables, but it is certainly not standard practice to obtain any objective record of a continuous performance of a pilot in a simulator for comparison with a simular record obtained in the air. As Odle and others pointed out, an additional complication arises from the fact that aircraft themselves are highly individual machines. No two fly exactly alike and a given aircraft may change in its handling characteristics with time. Therefore, an aircraft of a given type does not represent a completely stable reference for the evaluation of a simulator.

It is surmised that pilots tend to be influenced by "face validity." This is a term which is usually employed to characterize the extent to which a simulator provides detailed replication of all aspects of the actual vehicle. Some of the refinements of the simulation which make it seem highly realistic in appearance to someone seated in the pilot's seat may be of little real consequence with respect to the job of controlling the device. These elements may be extremely important for nurturing the illusion of reality at a superficial level, but could conceivably give rise to relatively favorable subjective evaluations of a device, certain fundamental aspects of which were seriously incorrect.

The ultimate criterion of any simulator to be employed for training must be the extent to which skills learned by its use can be transferred to the actual task for which training was undertaken in the first place. That is, if after an appropriate number of hours of simulator training, a pilot can fly the aircraft which the simulator was intended to represent without flaw, then the simulator is a success. Otherwise, it cannot be considered so. On these terms, many simulators now being used by the airlines for transition training are indeed successful. Questions arise as to their adequacy for recurrent training as discussed in an earlier memorandum.

Simulators used for experimental work, for development and design pose a much more difficult problem with respect to their evaluation and can only be assessed on an ex post facto basis in terms of the accuracy of predictions which are based on their use.

Questions were raised as to whether pilots would accept simulators if they, the pilots, did not consider them realistic, even though they might be efficient for training. Both Russell and Vogeley pointed out that if the simulators were indeed effective for training, pilots would have little choice and would accept the simulators in any case, purely on the basis of the practical demonstration that they work.

3. Analytic techniques for the evaluation of simulators and the characteristics which they must embody

A major question for any simulator designer concerns the nature of the fundamental cues which are employed by a pilot in the control of an aircraft. It was suggested by Held and others that this issue may be attacked by measurement of performance in a simulation as accurate as can be made or in actual flight under circumstances where elements of information provided to the pilot are selectively removed, or, in other words, various of the several redundant feedback loops are selectively interrupted. If it is desired to eliminate certain information but to retain motion cues, such an approach probably would have to be done in an aircraft. On the other hand, for the elimination of the motion cues, it would be necessary to employ a simulator. In this instance, it would be virtually impossible to eliminate just motion cues selectively while retaining all of the others with complete fidelity.

Smith suggested that information might be obtained by an attempt to degrade systematically various dimensions of information which are ordinarily available to the pilot. In the visual realm, these might include accuracy of the size of elements in the visual world, their clarity or resolution and the nature of relative visual motions. Actually, as Vogeley pointed out, efforts have been conducted over the years to show the way in which pilot's performance will be degraded by systematically decreasing the information available to him or somehow systematically increasing the complexity of the task confronting him. Unfortunately for these investigations but perhaps fortunate for the primary task (flying aircraft) pilots are able to compensate remarkably well for reductions of information or increases in task complexity. It is often possible to introduce incredibly great degradations in information feedback with no detectable change

in pilot performance. Then, at some critical level, performance is suddenly and completely disrupted. Thus the refined, systematic alterations in the task yield no information as to their individual significance to the pilot for his performance.

McCusker raised a question as to the possible value of physiological indices of pilot's condition. Such parameters as heart rate, respiration, psychogalvanic reflex and other physiological indices may be recorded. It is possible that these will show gradual changes as the task is made more difficult, even though the overall performance does not show degradation. Regan indicated that a valuable measure may be muscle tension. This may increase as task difficulty increases, even though there is no measureable change in performance.

Recently there has been considerable interest in the possibility of measuring the point of regard of the pilot continuously during the performance of maneuvers, such as landing. If information could be obtained as to just where he is looking as the landing proceeds, including flight instruments as well as the external visual world, better information would be available as to just what he needs to know at various stages in the task. Muckler suggested that the pilot will be found to be looking between instruments on some occasions and that in general he will be attempting to integrate an overall picture. That this is more difficult to do from a conventional instrument display than from a view of the outside world, at least under some conditions, is attested by the fact that helicopter pilots find it virtually impossible to maintain a stable hover without outside visual reference. Vogeley suggested that it might be of interest to record eye movements and points of regard for pilots who are flying a new simulator. This might provide information when compared with reference data obtained in aircraft as to the fidelity of the simulation.

The ability of pilots to take off and, particularly, land aircraft under conditions of reduced visibility certainly provide proof that a completely undegraded view of the visual world is unnecessary for satisfactory performance. To just what extent visibility may be degraded before pilots will consider the situation too difficult to attempt a landing has been studied systematically by the Air Force as reported by Odle. Films were made of landings performed under a variety of conditions of visibility. The landings were actually controlled by an autopilot. Pilots observing the films were asked to make a decision as to whether a landing was feasible under the various conditions represented. There

was some agreement as to the limiting conditions. There was also some consternation on the part of pilots unaware that an autopilot was being used when the film showed that the landing was carried out, even though limiting conditions had been exceeded.

Regan stated that evaluation of the nature of carrier landing with changing conditions of visibility indicated no change in average performance but an increase in the variability of performance.

It seems fair to conclude that additional information is needed as to just what a pilot is doing during various stages of such significant maneuvers as landing. As McCusker pointed out, the pilot himself, although quite capable of performing in the situation, may be completely incapable of telling you just what he has done.

4. The nature of simulation techniques

Muckler and others suggested that the purpose of a simulator should not be to evoke ecstatic responses from pilots as to how realistic the device may be. The purpose of the simulator is to provide a basis for training which will carry over to performance in an aircraft. Therefore, it may not be important as to whether the information provided the pilot is identical with that which he will obtain in the aircraft, provided the experience results in high transfer of training. We know, for example, that we cannot simulate the motion of an aircraft in the three-dimensional world accurately unless the simulator moves in the same fashion, i.e., becomes an aircraft. This is impossible. It is not completely unreasonable to suggest that improvement in simulators may be accomplished by exaggerating some of the characteristics of the simulator with respect to those which might be encountered in aircraft. More work should be done to assess this possibility.

There are a variety of possibilities associated with the way in which motion cues are introduced in simulators. Vogeley pointed out that in the VAMP simulations which included some jitter from the motion picture filmstrips employed, pilots found the situation very unrealistic. However, when some mechanical vibration was introduced into the system, the jitter was no longer disturbing. It was not necessary that the jitter in the visual display and the mechanical vibration or jostling of the pilot be correlated. It may be expected that there will be interesting interactions among motion and visual aspects of the display. Held mentioned

that recent electrophysiological studies have demonstrated that vestibular and visual inputs may result in identical responses within the nervous system. He raised the question as to whether visual inputs might not therefore be considered as possible substitutes for vestibular inputs. This is indeed a possibility worth exploring. It must be remembered, however, that identity of response at some point in the nervous system as a result of isolated visual or vestibular inputs does not mean that one can be substituted for the other for the enhancement of realism. In fact, a major problem in simulation is to maintain "compatibility" between visual and vestibular simulations. Without such compatibility, the probability of vertigo and nausea is materially increased. (As used here, "compatibility" refers to a correspondence of visual and vestibular inputs as they are usually encountered in the real world. That is, dramatic changes in visual motion do not occur without motion of the head, and visual and vestibular inputs are, under these circumstances, "compatible." The motions of a ship become disturbing when the horizon is not visible such that the visual motions cannot be evaluated in terms of a stable reference. The seen motions of the visual world from a roller coaster or a careening automobile on film are actually more disturbing than would the same visual inputs be were the observer in the moving vehicle.) Muckler and Regan both emphasized the potential value of more careful determinations of just what a simulator is to accomplish. It is probable that a number of "part-task" simulators could be used for training in some segment of an overall task where the simulator would be very much simpler and less expensive and could be used more efficiently. A completely comprehensive simulation can only be used for one aspect of a task at a time, although it has the capability of being used for all aspects. In addition, it is extremely expensive. Only one trainee can use it at a time and if, by reason of its expense, it is a unique item, or one of a very few devices, then a number of trainees will have to wait for access to the device. A larger number of part-task simulators could be acquired for the cost of complete simulation and a larger number of individuals could be trained simultaneously. In addition, as Regan pointed out, closed-loop simulation is not necessary for satisfactory training in all aspects of tasks which must be performed by pilots. Open-loop simulations may be satisfactory for some tasks. Open-loop simulations are simpler and cheaper and should be given consideration.

Where fairly complex simulations of the whole task are required, it may be desirable, as suggested by Collins, to simulate the external visual world with the aid of both a

three-dimensional model and a computer-generated display. The three-dimensional model, scanned by a television pick-up, might serve for the simulation of the real world of an airport, while the computer-generated display could provide a simulation of gross terrain. The computer-generated display has the advantage of permitting the inclusion of a wide variety of different airports on one simulator with ready interchangeability from one to another. Simulation of the visual world for cross-country flight is probably not very important for commercial applications but, according to Odle and McCusker, is important for a variety of military training applications.

5. A theory of visual information processing in aircraft landings

Arthur Vogeley presented some analyses of the aircraft landing problem relative to the way in which a pilot derives information from the visual world during performance of this maneuver. His thesis is based on the concept that an important cue for initiation of flair, prior to touch down, is the increase in rate of streaming of elements of the visual world outside the aircraft. This rate change will vary with glide path angle, air speed and altitude. At a certain point during landing, a qualitative difference in appearance of the streaming pattern may be discriminated. An analytic evaluation of the situation for several aircraft has indicated that this kind of cue could conceivably be of fundamental importance. Vogeley does not argue that this kind of cue is essential for landing when other cues are available. He is of the opinion, however, that it may be of more critical importance than other cues under limiting conditions. His thesis would appear to merit further evaluation. A demonstration that the landing pattern of the 747, coupled with a restriction in vertical visibility, make it impossible for the pilot to observe the streaming effect at the critical point, makes an early evaluation of this theory highly desirable. It is hoped that Vogeley will be able to prepare a technical report of the substance of his presentation at the meeting for early dissemination and review.

6. Computer-generated displays at General Electric

On the evening of January 13, the Working Group went to the general Electric plant at Daytona Beach and was given an excellent presentation by Mr. James Zimmerman and several of his colleagues. This included a description of the program at General Electric for development of computer-generated displays, both of the real world and of radar information,

motion pictures and demonstrations of actual equipment. Interestingly, General Electric had incorporated some of the films that were made by the Air Force under the direction of Major Odle for comparison with its own computer-generated displays of airports under various weather conditions. The trip to General Electric provided an excellent opportunity for a number of members of the Working Group to become more familiar with the potentials of computer-generated displays.

H. Attendance at the meeting of Working Group 34, January 13, 1972.

Members

John Lott Brown, Chairman	University of Rochester
William Benson, Secretary	NAS-NRC Committee on Vision
Carter Collins	Smith-Kettlewell Institute of Visual Sciences
Richard Held	Massachusetts Institute of Technology
Gene E. Lyman	National Aeronautics & Space Adm.
Frederick A. Muckler	Manned Systems Sciences
James J. Regan	Naval Training Deveice Center
Stanley W. Smith	Ohio State University

Guests

Capt. Robert McCusker	USAF Instrument Pilot Instructor School
Maj. Max L. Odle	USAF Instrum..nt Pilot Instructor School
Joseph A. Puig	Naval Training Device Center
M.E. Russell	Federal Aviation Administration
A.W. Vogeley	National Aeronautics and Space Adm.

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13 ABSTRACT

Flight simulators have now been in use for many years and their value has been amply proven. Many of today's simulators are very expensive, but they can pay for themselves by decreasing the cost and increasing the safety of learning to fly complex and expensive modern aircraft. Some aspects of aircraft control depend on exterior view from the aircraft to the outside visual world. Training in these aspects of flight in a simulator therefore requires that the visual world be simulated to the extent that cues derived from it need to be employed by the pilot. There are a number of maneuvers that cannot be performed without direct visual contact under normal circumstances in commercial as well as in military aviation. The importance of including a simulation of the external world is now acknowledged. Unfortunately, there is currently no solid scientific basis for cataloging visual cues with respect to their importance in aircraft control. In consequence, current efforts to create appropriate visual simulations run the gamut from efforts to create appropriate visual simulations run the gamut from efforts toward almost complete replication of the visual world to highly schematized, two-dimensional perspective displays on cathoderay tubes. The report summarizes information gathered by working group of the NAS-NRC Committee on Vision and recommends research topics, techniques, and strategies that the working group agreed should receive more attention.

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